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Performance and Cost-effectiveness of Chip Seal and Microsurfacing in Flexible Pavements

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PERFORMANCE AND COST-EFFECTIVENESS OF CHIP SEAL AND MICROSURFACING IN FLEXIBLE PAVEMENTS

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

By
Mohammad Zobair Ibne Bashar
B.Sc., Islamic University of Technology, 2014
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To my lovely wife for her endless love and support.

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ABSTRACT

Chip seal and microsurfacing are pavement maintenance activities typically used in relatively low traffic roads with the aim to reduce the rate of deterioration and to defer the need for costly rehabilitation activities. Chip seal is widely used in Louisiana, and Louisiana's \$6.3 million microsurfacing program is amongst the largest microsurfacing programs in the United States. As these surface treatments seal the road surface, the effectiveness of this treatment in such a setting has been a concern in recent years by linking it to moisture damage caused by the trapped moisture underneath the pavement. Furthermore, the cost-effectiveness and optimal timing of chip seal and microsurfacing applications are also not well established for the South-Central United States.

The primary objective of this study was twofold. First, the short and long-term performances of chip seal and microsurfacing treatments were evaluated as related to the pre-treatment conditions of the pavement. Performance curves were developed to assess the cost-effectiveness of the treatment. Effectiveness models in conjunction with the cost-benefits of the projects were used to identify the optimum timing for this preventive maintenance activity. Second, treated sections were evaluated to assess whether chip seal or microsurfacing significantly contribute to moisture damage. Field performance of 51 chip sealed and 28 microsurfaced sections were monitored for at least eight years. Long-term pavement performance data were used to quantify the benefits of chip seal and microsurfacing treatments in terms of the appropriate pavement performance indicators for the specific treatment type.

Results indicated that chip seal is most effective in reducing cracking intensity in the pavements, and microsurfacing is most effective in addressing rutting damages as compared to the other performance criteria. Chip seal extended the service life by 6.5 to 10.4 years and for microsurfacing, the service life extensions were observed to be 4.9 to 8.8 years. The effectiveness was found to be optimum when the treatment is applied to pavements with pre-treatment conditions ranging from 70-75 and 80-85 for chip seal and microsurfacing, respectively. No significant evidence was found indicating chip seal or microsurfacing being the primary factor contributing to moisture damage of the pavements.

CHAPTER 1. INTRODUCTION

Pavement maintenance and rehabilitation activities have received increased interests in recent years as compared to the design and construction of new pavements. A growing number of agencies including the Louisiana Department of Transportation and Development (LaDOTD) focuses more on their maintenance programs as these timely maintenance activities arrest initial deteriorations, reduce the rate of deterioration, and defer costly rehabilitation activities (Temple et al. 2002). Historically, thin overlays and resurfacing have been the most common preventive maintenance activities, which are applied to pavements exhibiting age-related distresses (Kiefer et al. 2017; Rajagopal 2010). If the structural capacity of the existing pavement is adequate to support future traffic loads, chip seals, micro-surfacing and similar surface treatments are widely used due to their low initial costs and convenient construction process (Gransberg 2005, 2006).

Chip sealing, also referred to as Asphalt Surface Treatment (AST) in Louisiana, is carried out by spraying asphalt emulsion or hot bitumen on the existing roadway surface, followed by the application of a layer of crushed aggregates (Labi et al. 2004; Louisiana Department of Transportation and Development 2016). Chip seals are typically favored on relatively low traffic roadways with the aim of reducing the permeability of the pavement surface, improve skid resistance, eliminate raveling, and retard oxidation (Rajagopal 2010). Bleeding and early loss of aggregates are the most commonly observed distresses associated with chip seal treatments (Gransberg 2005; Gransberg and James 2005). Chip seal is popular in the United States as its cost is one-fourth to one-fifth the cost of a regular Asphalt Concrete (AC) overlay.

Microsurfacing is a mixture of crushed aggregate, asphalt emulsion, water, polymer additive, and mineral fillers to correct wheel ruts, improve surface friction, and extend pavement service life (Gransberg 2010; Hein et al. 2003). It is usually a single aggregate thick and is placed as a thin lift of mixture typically containing 82 to 90% aggregate, 1.5 to 3.0% mineral filler, and 5.5 to 9.5% residual asphalt (Morian 2011; Peshkin et al. 2004). Microsurfacing has been found to be equally effective for both low and high-volume roadways. It also allows rapid opening of the roads to traffic, which makes it an effective preventive maintenance technique (Broughton et al. 2012; Erwin and Tighe 2008). The major challenge in microsurfacing is that it requires special equipment for application, which makes it an expensive form of preventive maintenance as compared to other common surface treatments such as chip seal or slurry seal treatment (Morian 2011).

1.1. Problem Statement

While chip seal treatments have been widely used in Louisiana, only a few studies have been conducted to methodically evaluate the effectiveness of these treatment activities in hot and humid climates such as Louisiana (Ali and Mohammadafzali 2014; Temple et al. 2002). Evaluation of both long-term and short-term effectiveness is vital for pavement asset management. Quantification of long-term benefits is more useful when dealing with maintenance strategies, while short-term benefits, such as immediate improvements in distress indices, extension in pavement service life and trend of deterioration after treatment are more valuable while evaluating the performance of individual treatment activities (Labi et al. 2004).

On the other hand, environmental conditions in Louisiana with high groundwater table and heavy rainfall conditions throughout the year make the pavements highly vulnerable to water entrapment and moisture damage. As microsurfacing seals the road surface completely, the effectiveness of this treatment in such a setting has been a concern in recent years by linking it to

moisture damage caused by the trapped moisture underneath the pavement. Furthermore, the cost-effectiveness and optimal timing of microsurfacing applications are also not well established for the South-Central United States. Proper knowledge of performance and cost components of the surface treatments under these conditions will allow the associated pavement maintenance agencies to set up a more reliable schedule and realistic budget for the maintenance and rehabilitation activities (Labi et al. 2006). The questions that need to be answered as related to the aforementioned problem statement are as follows:

- How do these treatment activities affect the performance of the pavement in the short and long terms?
- What are the factors that influence the performance of these preventive maintenance activities?
- When is the appropriate time to apply these treatments?
- Are these treatments cost-effective?
- Do these treatments significantly contribute towards the moisture damage of the pavements?

1.2. Research Objectives

The goal of this research is to evaluate the performance and cost-effectiveness of chip seals and microsurfacing applied to flexible pavements in Louisiana. To achieve this goal, the following objectives of this study are proposed:

- a) Quantify the short and long-term effects, if any, of chip seal and micro-surfacing treatments on pavement conditions (i.e., cracking, roughness, and rutting);
- b) Assess the influence of different pavement factors on the performance of chip seal and microsurfacing treatments;
- c) Identify the optimum timing for chip seal and microsurfacing based on traffic and pre-treatment conditions of the pavement; and
- d) Quantify the cost-effectiveness of these treatment activities.
- e) Assess whether chip seal and microsurfacing significantly contribute to moisture damage.

1.3. Research Approach

The research approach adopted in this study consists of completing the following main tasks:

1.3.1. Literature Review (Task 1)

A comprehensive literature review was conducted to review the following topics:

- a) Pavement preservation practices in the US;
- b) State of practices in using chip seal and microsurfacing as a preventive maintenance activity;
- c) Pavement distresses associated with different types of pavements and their treatments;
- d) Performance models;
- e) Chip seal and microsurfacing effectiveness studies; and
- f) Cost-effectiveness evaluation techniques for these preventive maintenance activities.

1.3.2. Data Collection (Task 2)

Louisiana DOTD databases including the Pavement Management System (PMS), Highway Needs, Tracking of Projects (TOPS), Material Testing System (MATT), letting of projects (LETS) and Project and Highway Information inventory will be used to collect the data required for a detailed performance evaluation and economic analysis. The pavement condition data, such as cracking, roughness, patching and rutting measurements are recorded biennially using the Automated Road Analyzer (ARAN[®]) and the results are reported every 0.1 miles. For flexible and composite pavements, the random cracking index encompasses all random cracks, which include thermal transverse, reflective transverse, longitudinal, block, and cement-treated reflective cracks. The temperature and precipitation data will be extracted from the National Oceanic and Atmospheric Administration (NOAA) database

1.3.3. Select the Candidate Projects (Task 3)

A preliminary list of chip seal and microsurfacing projects will be prepared using the Tracking of Projects (TOPS) and Letting schedule (LETS) databases. To determine the exact location, length, and the date of the chip seal application, video logs will be reviewed using the VisiWeb software.

To facilitate quantification of treatment effectiveness and plotting of the polynomial pavement performance model, a candidate project must meet the following project acceptance criteria:

- A road segment should have pavement condition data available for a minimum of four cycles before and four cycles after the application of chip seal so that non-linear models can be fitted through the data points.
- Distress data should follow a decreasing pattern over the years except for the year after treatment, which should exhibit an increase in the distress index value.

1.3.4. Model Pavement Conditions as a Function of Time (Task 4)

Several studies have used a polynomial approach to model pavement conditions (Khattak et al. 2009; Lu and Tolliver 2012; Morian 2011). In this study, both pre and post-treatment conditions will be represented by polynomial models as shown in Equations (1.1) and (1.2); see Figure 1.1:

$$f_{pre}(t) = a_1 t^2 + b_1 t + c_1 \quad (1.1)$$

$$f_{post}(t) = a_2 t^2 + b_2 t + c_2 \quad (1.2)$$

where,

a_1, b_1, c_1, a_2, b_2 and c_2 = parameters representing the pavement condition and deterioration rates over time for pre and post-treatment performance models; and

t = time in years.

According to the model, the condition of a pavement will deteriorate over time following the curve AC as shown in Figure 1.1; however, if any treatment is applied at time t_i (point B), the pavement condition index will increase to point D. This immediate increase in pavement condition index following a treatment activity is known as a performance jump. After the jump, the deterioration pattern will follow the curve DE. The time is set equal to zero at point D for the post-treatment performance curve.

The pre and post-treatment performance curves will reach the threshold at different times, which can be estimated using Equations (1.3) and (1.4):

$$SL_{pre} = \frac{-b_1 - \sqrt{-b_1^2 - 4a_1(c_1 - T)}}{2a_1} \quad (1.3)$$

$$SSL_{post} = \frac{-b_2 - \sqrt{-b_2^2 - 4a_2(c_2 - T)}}{2a_2} + t_i \quad (1.4)$$

where,

SL_{pre} = pavement age with no treatment to a threshold;

SL_{post} = pavement age with treatment to a threshold;

T = threshold value for pavement condition index; and

t_i = time of the treatment activity in years.

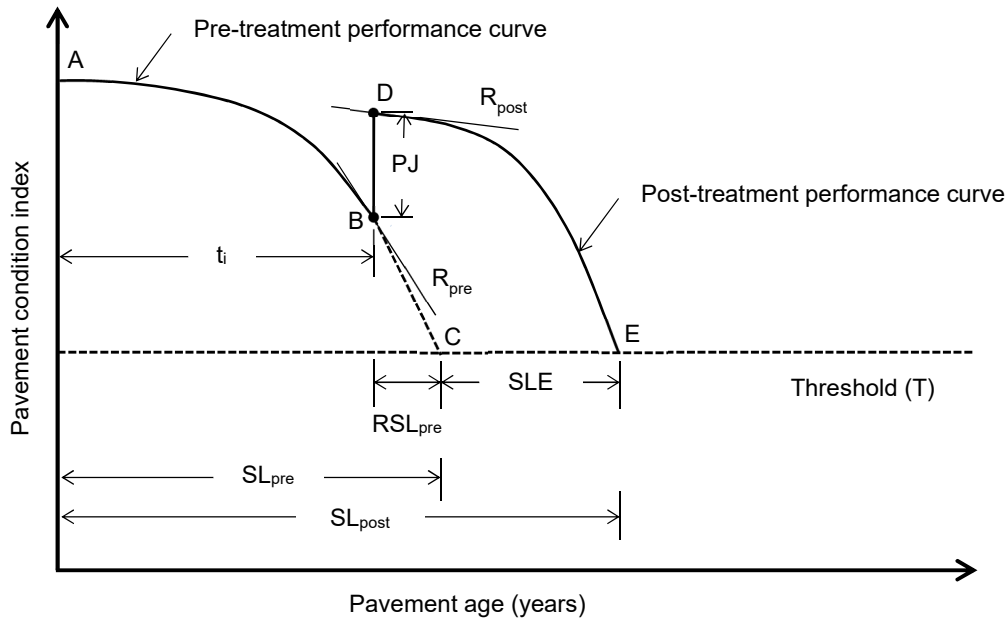


Figure 1.1. Pre and post-treatment performance curves assuming polynomial deterioration patterns

1.3.5. Compute the Effectiveness Measures (Task 5)

The initial effects, if any, of the chip seal and microsurfacing treatment on roughness, cracking, rutting and overall condition of the pavement will be evaluated in terms of performance jump and deterioration rate reduction. Long-term effects of the treatment will be evaluated in terms of service life extension (SLE).

Service life extension is given by the difference between pre and post-treatment service lives:

$$SLE = SL_{post} - SL_{pre} \quad (1.5)$$

where,

SLE = service life extension in years.

Pavement condition just before and after the treatment can be estimated as follows:

$$f_{pre}(t_i) = a_1 t_i^2 + b_1 t_i + c_1 \quad (1.6)$$

$$f_{post}(0) = c_2 \quad (1.7)$$

Performance jump (PJ) is calculated by subtracting equation (1.6) from equation (1.7).

$$PJ = c_2 - (a_1 t_i^2 + b_1 t_i + c_1) \quad (1.8)$$

Deterioration rate reduction (DRR) refers to the slowing down of the pavement deterioration, which can be estimated by calculating the difference between rates of deterioration of the pavement just before and after the treatment as follows:

$$R_{pre} = \left. \frac{df_{pre}(t)}{dt} \right|_{t=t_i} = 2a_1 t_i + b_1 \quad (1.9)$$

$$R_{post} = \left. \frac{df_{post}(t)}{dt} \right|_{t=0} = b_2 \quad (1.10)$$

$$DRR = R_{post} - R_{pre} \quad (1.11)$$

where,

R_{pre} and R_{post} = rate of deterioration of the pavement just before and after the treatment; and

DRR = deterioration rate reduction.

1.3.6. Evaluate the Cost-effectiveness of the Preventive Maintenance Activities (Task 6)

To assess the cost-benefits of chip seal and microsurfacing treatments, a cost-effectiveness analysis will be conducted. The performance of chip seal or microsurfacing applied at a level before reaching the threshold will be compared with the performance of the existing pavement without any maintenance activity, i.e., with the ‘do nothing’ baseline performance model.

1.3.7. Assess the Effects of Treatment Activities on Moisture Damage of the Pavements (Task 7)

Moisture damage is a significant distress that affects the overall performance of asphalt pavements in Louisiana. Moisture damage is critical as it only appears at the surface after detrimental damage has already progressed in the underlying pavement layers. As surface treatments such as chip seal and microsurfacing seal the pavement surface, it will not be illogical to suspect that it may trap moisture underneath the pavement causing the moisture to gradually cause damage in the long-term. To assess whether these treatments do really contribute to moisture damage, a comparative study of the sections with moisture damage will be conducted.

1.4. Scope

Field performance of 51 chip sealed and 28 microsurfaced sections receiving treatments between 2003 and 2010 were analyzed. Long-term pavement performance data was used to quantify the benefits of chip seal and microsurfacing treatments in terms of the appropriate pavement performance indicators. In addition, a comparative study of the treated sections was carried out to assess the effects of these surface treatments on moisture induced damage of the pavements. A ranking of the factors influencing the performance of these treatment was determined to facilitate a more accurate treatment timing and selection of the candidate projects. Optimum treatment timing conditions were proposed to incorporate into the existing pavement performance models that trigger the need for a rehabilitation project.

1.5. Organization of the Thesis

This thesis is divided into six chapters. Following this introductory part is Chapter 2, which reviews the literature regarding pavement preservation practices in the US, state of practices in using chip seal and microsurfacing as a preventive maintenance activity, pavement distresses associated with different types of pavements and their treatments, pavement performance models, and the effectiveness of these treatment activities. Chapter 3 describes the research approach of this study along with the descriptions of performance indicators and the measures of effectiveness. Details of the selected projects and the data collected have been sighted in Chapter 4. The results of the performance and moisture damage analysis have been presented in Chapter 5. In addition, it also lists the optimum treatment timing conditions based on the quantified benefits. Chapter 6 summarizes the outcomes of the research. Recommendations based on the findings of this study has also been presented in this chapter. The reference and vita sections conclude this thesis.

CHAPTER 2. LITERATURE REVIEW

2.1. Pavement Preservation

Federal Highway Administration (FHWA) defines pavement preservation as a “work that is planned and performed to improve or sustain the condition of the transportation facility in a state of good repair.” Preservation activities are undertaken to restore the overall condition of a transportation facility and these activities generally do not add capacity or structural value to the existing pavements (“Guidance on Highway Preservation And Maintenance and Preservation” 2016). The main components of pavement preservation are shown in Figure 2.1.

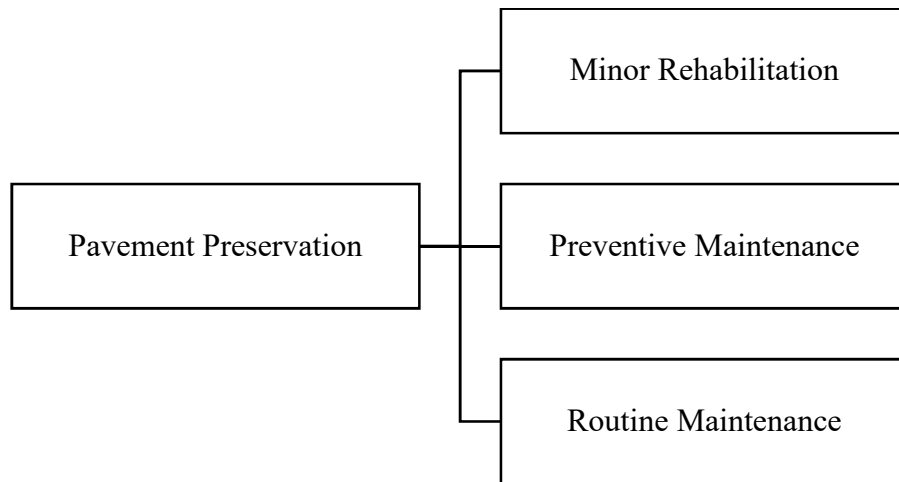


Figure 2.1. Components of pavement preservation (“Pavement Preservation Definitions” 2005)

Minor rehabilitations involve the non-structural enhancements applied to the existing pavements to eliminate the age-related, top-down surface cracks that develop in pavements due to the environmental exposure. Routine maintenance is planned and performed on a routine basis in order to maintain and preserve the condition of the highway system at a satisfactory level of service. Preventive maintenance, on the other hand, is a planned strategy of cost-effective treatments typically applied to the surface or near surface of structurally sound pavements with the aim to extend service life of these pavements. Each of the treatments has distinctive purposes of application, which is summarized in Table 2.1.

2.2. Preventive Maintenance Treatments

The most common types of distresses exhibited by flexible pavements include rutting, fatigue, shrinkage and thermal cracking, bleeding, roughness, raveling, and weathering. Typical preventive maintenance tools available to address these issues related to the bituminous-surfaced pavements include:

- **Crack Filling:** A maintenance procedure, which is carried out to reduce water infiltration and to reinforce the adjacent pavement by placing materials into cracks that do not experience significant horizontal movements (>0.1 in.) (Hicks et al. 1999).

- Crack Sealing: A maintenance tool involving the placement of sealant materials into working cracks specific configurations to prevent the intrusion of incompressible particles and water into the cracks (Hicks et al. 1999).
- Fog Seals: A light spray that is primarily applied to coat, protect, and/or rejuvenate the existing asphalt binder which reduces raveling and enriches dry and weathered surfaces (Peshkin 2004).
- Slurry Seals: A mixture of well-graded fine aggregate, slow setting emulsified asphalt, mineral filler, and water, which is especially helpful in filling and sealing cracks in old pavements, restoring uniform surface texture and preventing intrusion of water and dusts into the cracks (Hicks et al. 1999).
- Scrub Seals: Peshkin defined scrub seal as “a layer of polymer-modified asphalt that is applied in the voids and cracks of an existing Hot Mix Asphalt (HMA) pavement, followed by the application of sand or small-sized aggregate” (Peshkin 2004).
- Microsurfacing: An improved version of the slurry seals that involves laying a mixture of 100% crushed aggregate, asphalt emulsion, water, polymer additive, and mineral fillers to correct wheel ruts, improve surface friction, and extend pavement service life (Gransberg 2010; Hein et al. 2003)
- Chip seals: A pavement surface treatment in which one or multiple layers of crushed aggregates are glued to a distressed pavement surface using an asphalt emulsion (Peshkin 2004).
- Thin overlay: Thin HMA overlays are usually 0.75 to 1.50 in. thick and are usually applied to extend service life, correct surface distresses, and improve ride quality (Peshkin 2004).
- Ultrathin HMA Courses: Ultra-thin HMA overlays are usually a thin (0.4 to 0.8 in.), gap-graded layer of HMA placed on top of a special polymer-modified asphalt layer, which is usually placed in a single pass using a paver (Peshkin 2004).

Table 2.2 relates various distresses with the appropriate treatment strategies. If the pavement condition survey identifies structural deficiencies in the pavement, it is more likely to be listed as a candidate project for rehabilitation or reconstruction (Gransberg 2005, 2006).

This study primarily focuses on the effectiveness of chip seal and microsurfacing treatments applied to flexible pavements. Therefore, these two preventive maintenance treatments are discussed in more details in the following sections.

2.3. Chip Seal

2.3.1. Overview

Chip seal is a surface treatment, which is carried out by spraying cold asphalt emulsion or hot bitumen on the existing roadway surface, followed by spreading a layer of crushed aggregates (Labi et al. 2004). Low cost and convenient construction process have made this technique popular throughout the United States. Chip seals are usually applied on relatively low traffic roadways with the aim to improve the impermeability of the pavement surface, improve skid resistance, eliminate raveling and retard oxidation (Rajagopal 2010). Figure 2.2 illustrates the before and after of applying chip seals to a pavement surface.

Table 2.1. Intended purposes of pavement preservation activities (“Pavement Preservation Definitions” 2005)

	Type of Activity	Increase Capacity	Increase Strength	Reduce Aging	Restore Serviceability
	New Construction	✓	✓	✓	✓
	Reconstruction	✓	✓	✓	✓
	Major (Heavy) Rehabilitation		✓	✓	✓
	Structural Overlay		✓	✓	✓
	Minor (Light) Rehabilitation			✓	✓
	Preventive Maintenance			✓	✓
Pavement Preservation	Routine Maintenance				✓
	Corrective (Reactive) Maintenance				✓
	Catastrophic Maintenance				✓

Table 2.2. Appropriate strategies for different distress types (Hicks et al. 1999)

Pavement Distress	Crack Sealing	Fog Seal	Microsurfacing	Slurry Seal	Cape Seal	Chip Seal	Thin HMA overlay	Mill or Grind ¹
Roughness (stable)			X		X		X	X
Roughness (unstable)							X	
Rutting			X				X	X
Fatigue Cracking ²		X	X	X	X	X	X	
Longitudinal & Transverse Cracking	X		X	X	X	X	X	
Bleeding			X			X		X
Raveling		X	X	X	X	X		

Key: X = Appropriate strategy

¹ This is a corrective maintenance technique

² For low severity only; preventive maintenance is not applicable for medium to high severity fatigue cracking



Figure 2.2. Before and after the application of chip seals as a surface treatment

2.3.2. Types of chip seals

To address different distresses under varying traffic and environmental conditions, chip seals are applied in different configurations. Several types of chip seals, which are in use today include:

- **Single chip seal:** In a single chip seal, the binder is applied to the pavement surface followed by an application of a single layer of aggregate. This is the most cost-effective form of chip sealing which is suitable for improving skid resistance of the wearing surface, arresting raveling and sealing minor cracks (Gransberg and James 2005; Testa and Hossain 2014; Transportation 2007).
- **Multiple chip seal:** When two or more consecutive single chip seals are applied on the same pavement surface, it is known as multiple chip seal. Multiple chip seals are usually used on roads having a greater traffic volume. The use of smaller aggregates in the upper layer helps reducing traffic noise (Gransberg and James 2005; Peshkin 2004; Testa and Hossain 2014).
- **Sandwich seal:** It involves the application of a layer of larger aggregates, followed by the spraying of asphalt emulsion and then covering the layer with smaller aggregates (choke stones) (Gransberg and James 2005; Peshkin 2004).
- **Cape seal:** These are conventional chip seals covered with slurry seals which offer a better shear resistance than the asphalt (Peshkin 2004; Testa and Hossain 2014). According to Solaimanian et al., if cape seal is applied properly, it offers “a smooth, dense surface, one having good skid resistance and a relatively long service life” (Solaimanian and Kennedy 1998).
- **Racked-in seal:** This is a special type of chip seal where a layer of choke stone is applied above a single-course chip seal to protect any damage to the upper layer of the treatment. It is usually applied in areas with high turning movement of the vehicles (Gransberg and James 2005; Peshkin 2004).
- **Inverted seal:** Inverted seal is the type of double chip seal where smaller aggregates are applied first, followed by the application of binder and the larger aggregates goes on the top of the formation. It is usually applied in pavements exhibiting bleeding and non-uniformity in transverse surface texture (Gransberg and James 2005; Peshkin 2004; Testa and Hossain 2014).
- **Geotextile reinforced seal:** For extremely oxidized or thermal cracked surfaces, chip seals are reinforced using geotextile products to improve their performance. It involves the

application of a tack coat first, followed by applying the geotextile over the tack coat and a single chip seal is applied on the top (Gransberg and James 2005; Testa and Hossain 2014).

2.3.3. Types of binders used

Selection of an appropriate binder or emulsion for a specific type of chip seal plays an important role in the performance of the applied treatment (Transportation 2007). Binders exhibiting excellent adhesion properties are recommended as it is important for retaining aggregates during the early life of the treatment. Asphalt emulsions are most commonly used binder for chip seals. Rapid or medium setting emulsions are used for conventional chip seals to facilitate a quick reaction between the binder and the aggregate (Peshkin 2004). Polymer modified emulsions (PME) are used in the design of chip seals for heavily trafficked roads. Polymer modified emulsions offer better adhesion to the older surface, rapid bonding with aggregates and less susceptibility to temperature (Zaniewski and Mamlouk 1996). Other types of commonly used binder include performance graded (PG) asphalt, asphalt rubber binder, and rejuvenating emulsion. According to the Louisiana Standard Specifications for Roads and Bridges (2016), the binder should comply with the requirements specified in Table 2.3 and 2.4 for cold and hot application, respectively.

Choosing an appropriate binder for a specific chip sealing technique can help to increase the effectiveness of the surface treatment, as different combinations have been found to be effective in addressing different distresses. Table 2.5 illustrates the combinations of binders and chip seals to address different distress types.

2.3.4. Aggregate Selection

Type of the roadway, traffic volume, weather conditions, availability and the cost of the aggregates are the most important factor while selecting an appropriate type of aggregate for chip sealing. The compatibility of the aggregates with the binders should also be taken under consideration to achieve a sound design (Transportation 2007). The thickness of the chip seal and the amount of voids are largely dependent upon the choice of the aggregate. Reduction in the maximum aggregate size contributes towards the reduction of roughness and noise, but at the same time, it leaves smaller void spaces to be filled by asphalt, which requires more control over the application and lower binder application rate (Peshkin 2004). The Kansas DOT defines appropriate aggregates for chip sealing as single sized, clean, clay free, cubical shaped aggregates having a maximum dust content of 2% and a maximum abrasion loss of 45% (Testa and Hossain 2014). Table 2.6 summarizes the desirable aggregate properties for chip sealing as specified by the Montana DOT.

Louisiana DOT requires using crushed gravel, crushed stone, or lightweight aggregate for asphalt surface treatment purposes and the gradation of the aggregates should comply with Table 2.7.

Table 2.3. LaDOTD Asphalt Surface Treatment (AST) requirements (Cold Application) (Louisiana Department of Transportation and Development 2016)

	Course No.	AST TYPE A		AST TYPE B		AST TYPE C	AST TYPE D			AST TYPE E (Int. layer)
Aggregate		Lightweight, Crushed Stone		Lightweight, Crushed Stone		Lightweight, Crushed Stone	Lightweight, Crushed Stone, Crushed Gravel			Crushed Stone, Crushed Gravel
Agg. Friction Rating		I, II		I, II, III		I, II, III	I, II, III, IV			I, II, III, IV
Asphalt Emulsion		CRS-2P		CRS-2P		CRS-2P	CRS-2P			CRS-2P
Application Temp. Minimum Maximum		160°F 175°F		160°F 175°F		160°F 175°F	160°F 175°F			160°F 175°F
Number of Applications		2	1	2	1	1	3	2	1	2
Asphalt Emulsion Application Rates Per Course	1 2 3	0.39 0.29 —	0.41 — —	0.39 0.29 —	0.31 — —	0.41 — —	0.46 0.36 0.26	0.39 0.29 —	0.31 — —	0.39 0.29 —
Aggregate size and Application Rates Per Course	1 2 3	S2-0.0111 S3-0.0075 —	S2-0.0111 — —	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 — —	S1-0.0200 S2-0.0111 S3-0.0075	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 S3-0.0075 —

Table 2.4. LaDOTD Asphalt Surface Treatment (AST) requirements (Hot Application) (Louisiana Department of Transportation and Development 2016)

	Course No.	AST TYPE A		AST TYPE B		AST TYPE C	AST TYPE D			AST TYPE E (Int. layer)
Aggregate		Lightweight, Crushed Stone		Lightweight, Crushed Stone		Lightweight, Crushed Stone	Lightweight, Crushed Stone, Crushed Gravel			Crushed Stone, Crushed Gravel
Agg. Friction Rating		I, II		I, II, III		I, II, III	I, II, III, IV			I, II, III, IV
Asphalt Cement		PAC-15		PAC-15		PAC-15	PAC-15			PAC-15
Application Temp. Minimum Maximum		300°F 360°F		300°F 360°F		300°F 360°F	300°F 360°F			300°F 360°F
Number of Applications		2	1	2	1	1	3	2	1	2
Asphalt Cement Application Rates Per Course	1 2 3	0.30 0.23 —	0.31 — —	0.30 0.23 —	0.24 — —	0.31 — —	0.36 0.28 0.20	0.30 0.23 —	0.24 — —	0.30 0.23 —
Aggregate size and Application Rates Per Course	1 2 3	S2-0.0111 S3-0.0075 —	S2-0.0111 — —	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 — —	S1-0.0200 S2-0.0111 S3-0.0075	S2-0.0111 S3-0.0075 —	S3-0.0075 — —	S2-0.0111 S3-0.0075 —

Table 2.5. Combination of binder and chip seal to address specific distress type (Transportation 2007)

Binder/ Chip Seal Combination	Raveling	Aged Pavements	Bleeding/Flushing	Load Associated Cracks	Water Proofing	Climate-Associated Cracks	Heavy Traffic Volumes	Stone Retention	Improve Skid Resistance
PME/Single	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PME/Double	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PG/Single	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
PG/Double	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rejuvenating Emulsion/single	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes

Table 2.6. Desirable characteristics of aggregates for chip sealing (Bousliman et al. 1989)

Property	Specification
Maximum particle size	3/8"
Overall Gradation	Single size aggregates with uniform gradation
Particle shape	Cubical or pyramidal
Asphalt adhesion	>70%
Abrasion resistance	< 30%

Table 2.7. Gradation for Asphalt Surface Treatment (Louisiana Department of Transportation and Development 2016)

Sieve		Size 1		Size 1A	Size 2	Size 3
U. S.	Metric	Slag or Stone Aggregate (Size No. 5)	Crushed Gravel or Lightweight Aggregate	Slag or Stone Aggregate	All Aggregate	All Aggregate
1 1/2 inch	37.5 mm	100	100	100	—	—
1 inch	25.0 mm	90-100	95-100	100	—	—
3/4 inch	19.0 mm	20-55	60-90	85-100	100	—
1/2 inch	12.5 mm	0-10	—	25-40	95-100	100
3/8 inch	9.5 mm	0-5	0-15	5-15	60- 80	95-100
No. 4	4.75 mm	—	0-5	—	0-5	20-50
No. 8	2.36 mm	—	—	—	0-2	0-2
No. 2002	75 µm	0-1	0-1	0-1	—	—

2.3.5. Candidate Projects for Chip Seal

The issues that are usually addressed with chip sealing include moisture infiltration through the surface, longitudinal cracking, transverse cracking, block cracking, friction loss, and bleeding. Structurally deficient pavements are not candidates for chip sealing, as these thin surface treatments do not contribute towards the structural capacity of the pavements (Gransberg and James 2005; Preservation 2005).

Peshkin recommends the existing pavements with following conditions as a good candidate for chip sealing (Peshkin 2004):

- Longitudinal and transverse cracks having a width less than 6 mm.
- Oxidation and hardening of the asphalt surface.
- Weathering/raveling in which aggregate particles are not coming loose.
- Poor surface friction.
- Bleeding on the pavement surface.
- Fatigue cracking in which the cracks have not yet begun to interconnect and spall (however, the chip seal will not improve the structural capacity, and fatigue cracking may continue).
- Non-structural rutting having a depth less than 10 mm.

2.3.6. Weather limitation

Due to the extreme volatility and temperature susceptibility of asphalt emulsions, weather conditions play a major role in the ultimate performance of the applied chip seal (NCDOT 2015). Chip seal should not be applied on a wet surface. Louisiana Department of Transportation specifies that a pavement should be considered wet when it is visibly moist or when a one square foot piece of polyethylene film condenses moisture after being tightly placed on pavement surface for 15 minutes (Louisiana Department of Transportation and Development 2016). Hot applied AST should not be applied on a surface, which has experienced rainfall within the past last 24 hours. The direction of the wind is also important, especially while spraying emulsion with latex (Bousliman et al. 1989). If the air temperature is less than 60°F or there is any possibility that the temperature will fall below 60°F within 24 hours of the placement of the chip seal, it is better not to apply the treatment (Louisiana Department of Transportation and Development 2016).

2.4. Microsurfacing

2.4.1. Overview

Microsurfacing is the technologically improved version of the slurry seals that involves laying a mixture of 100% crushed aggregate, asphalt emulsion, water, polymer additive, and mineral fillers to correct wheel ruts, improve surface friction, and extend pavement service life (Gransberg 2010; Hein et al. 2003). Microsurfacing is usually a single aggregate thick and is placed as a thin lift of blended aggregates and emulsion (Morian 2011). Microsurfacing has been found to be equally effective for both low and high volume roadways and it allows rapid opening of the highways to traffic, which makes it an effective preventive maintenance tool (Broughton et al. 2012). However, the major challenge in microsurfacing is that it requires a special equipment for application, which makes it an expensive form preventive maintenance tool as

compared to chip seal or slurry seal treatment. Figure 2.3 illustrates the before and after of applying microsurfacing to a pavement surface.

Louisiana's \$6.3 million microsurfacing program is amongst the largest microsurfacing programs in the United States (2). Louisiana has a humid subtropical climate, characterized by long, hot, humid summers with heavy rainfalls throughout the year (average annual rainfall of 60 in.) where microsurfacing treatments primarily serve the purpose of waterproofing the pavement surface. Temple et al. investigated the performance of Louisiana's microsurfacing program in 2002 (8). The study analyzed treated sections for 60 months and detected significantly fewer cracks and substantial reduction in rutting after treatment. However, this study assessed the effectiveness of microsurfacing holistically and did not provide insights into the factors affecting the performance of microsurfacing in Louisiana.



Figure 2.3. Pavement images showing the before and after of microsurfacing application on a selected road segment

2.4.2. Types of Binder Used

Quick setting polymer modified emulsions are usually used in microsurfacing. CSS-1h-p binders are the most commonly used for microsurfacing. Other microsurfacing emulsions include CSS-1P, CSS-1h, CSS-1hP, CQS-1h, CQS-1hP, CRS-1P, CRS-2P, and Ralumac™ (Ali and Mohammadafzali 2014). Before the emulsification process, the polymer is blended or milled into the emulsion and the polymer modified emulsions must meet the requirements of AASHTO M208 or ASTM D2397 to be used in the microsurfacing process (Peshkin 2004). Typical emulsion properties have been summarized in Table 2.8. The following application rates should be used based on different traffic volume of the roads:

- For roads with low traffic volume: 10-20 lb./yd²
- For high volume roads: 15-30 lb./yd²

2.4.3. Aggregate selection

100% crushed stones such as slag, granite, limestone, and other high-quality aggregates are used in microsurfacing. According to the Basic Asphalt Emulsion Manual, an aggregate mix must pass the following standards to be used in microsurfacing (A Basic Asphalt Emulsion Manual 2004):

- Sand equivalent value, ASTM D 2419 (AASHTO T 176) = 60 minimum.
- Soundness, ASTM C 88 (AASHTO T 104) = 15% maximum using Na₂SO₄ or 25% maximum using MgSO₄

- Los Angeles abrasion loss, ASTM C 131 (AASHTO T 96) Grading C or D = 30% maximum.

The two most commonly accepted aggregate gradations for microsurfacing and recommended by the International Slurry Surfacing Association are presented in Table 2.9.

Table 2.8. Typical emulsion properties for microsurfacing (Caltrans 2009)

Tests on Emulsion	Typical Specification	Method
Viscosity, SSF @ 25°C, sec	15 – 90	AASHTO T 59
Settlement, 5 days, %	< 5	ASTM D 244
Storage Stability, 1 day, %	< 1	AASHTO T 59
Sieve Test, %	< 0.30	AASHTO T 59
Residue by Evaporation, %	> 62	California Test 331
Tests on Residue from Evaporation Test	Typical Specification	Method
Penetration, 25°C	40 – 90	AASHTO T 49
Softening Point, °C	> 57	AASHTO T 53
G* @ 20°C, 10 rad/sec, MPa	Report Only	AASHTO TP 5
Phase Angle @ 50°C, 10 rad/sec, PA(max) – PA base	Report Only	AASHTO TP 5
Stiffness @ -12°C, MPa, M-Value	Report Only	AASHTO TP 1
Torsional Recovery, %	> 18% (LMCQS-1h)	California Test 332
Polymer Content	> 2.5% (LMCQS-1h)	California Test 401

Table 2.9. Microsurfacing Aggregate Gradations (A Basic Asphalt Emulsion Manual 2004)

Gradation Type	II	III
General Usage	General resurfacing, sealing and renewal of surface friction	High volume roadway resurfacing, rut filling. Produces high-friction surfaces
Sieve Size	Percent Passing	Percent Passing
9.5 mm (3/8 in.)	100	100
4.75 mm (No. 4)	90-100	70-90
2.36 mm (No. 8)	65-90	45-70
1.18 mm (No. 16)	45-70	28-50
600 µm (No. 30)	30-50	19-34
300 µm (No. 50)	18-30	12-25
150 µm (No. 100)	10-21	7-18
75 µm (No. 200)	5-15	5-15
Residual Asphalt Content, % weight of dry aggregate	5.5-9.5	5.5-9.5
Application Rate, kg/m ² (lb/yd ²), based on weight of dry aggregate	5.4-9.1 (12-20)	8.2-13.6 (18-30)

2.4.4. Candidate projects

Public highway agencies use a wide variety of methods for selecting the appropriate projects for microsurfacing treatment. The primary factors that influence the selection process varies based on the time of the year when the treatment will be applied, climatic conditions, cost of the treatment, availability of funds and quality materials (Peshkin 2004). A survey of the US and Canadian public highway agencies indicated that providing a wearing course and preventing water infiltration were the main purposes of the agencies to choose microsurfacing in the US, whereas in Canada, the agencies used microsurfacing as a tool to prevent rutting, see Table 2.10. Distress modes that can primarily be addressed using microsurfacing include raveling, hairline cracks, rutting, and roughness. However, structural failures such as fatigue cracking, base failures, and plastic deformation of the HMA layers cannot be corrected using microsurfacing.

Caltrans Division of Maintenance defined the following properties as a requirement for a pavement to be chosen for a microsurfacing treatment (Caltrans 2009):

- Sound and well-drained bases, surfaces, and shoulders.
- Free of distresses, including potholes and cracking. These must be repaired before slurry application. Potholes should be filled and compacted several weeks prior to slurry surfacing. Emulsion crack filling should be done several months prior to slurry surfacing.

Table 2.10. Survey responses for microsurfacing responses logic (Peshkin 2004)

Reason for selecting microsurfacing	Number of responses	
	U.S.	Canada
Provide a surface wearing course	9	0
Prevent water infiltration	6	1
Oxidation	3	1
Raveling	3	2
Fill surface rutting	2	4
Improve stripping visibility	0	0
Distress (cracking)	1	0
Improve friction (skid) resistance	1	0

2.5. Performance Models

Performance models are used to predict the performance of the treatment activities with time. As not all distress mechanisms behave the same way over time, different forms of performance models have been introduced by the researchers in the past. Table 2.11 shows the most commonly used forms of performance models used in performance prediction of the treatment types.

Haider and Dwikat used an exponential IRI model to estimate the optimum timing for preventive maintenance activities (Haider and Dwaikat 2011). The proposed model, as shown in figure 2.4, was used to evaluate the effects of thin overlay, slurry seal, crack seal, and chip seal on the roughness of the pavements. The model can also be used to estimate the optimum timing of a treatment activity, jump in the pavement condition after treatment, and expected deterioration rates after the application of the treatments.

A significant number of national and international studies have been undertaken to predict the performance of preventive maintenance activities in the recent past. A wide range of performance indicators were used by the researchers to evaluate the effects of such activities on the short-term and long-term performance of the pavements. Table 2.12 summarizes the significant performance prediction models for preventive maintenance activities.

Table 2.11. Common pavement distress models (Khattak and Baladi 2015)

Form of equation (use)	Pavement distress type		
	IRI (exponential)	Rut depth (power)	Cracking (Logistic (S-shaped))
Generic equation (modeling)	$IRI = \alpha \exp(t\beta)$	$Rut = \gamma t^\omega$	$Crack = \frac{Max}{1 + \exp(\theta + \mu t)}$
Derivative (slope)	$\alpha\beta \exp(t\beta)$	$\gamma\omega t^{(\omega-1)}$	$\frac{Max \mu \exp(\theta + \mu t)}{[\exp(\theta + \mu t) + 1]^2}$
Integral (performance area)	$\left(\frac{\alpha}{\beta}\right) \exp(t\beta)$	$\frac{\gamma t^{(\omega+1)}}{(\omega + 1)}$	$Max \left\{ t \frac{\log[\exp(\theta + \mu t) + 1]}{\mu} \right\}$
Time to reach threshold (LE)	$t = \frac{\ln\left(\frac{Threshold}{\alpha}\right)}{\beta}$	$t = \exp\left[\frac{\ln\left(\frac{Threshold}{\gamma}\right)}{\omega}\right]$	$t = \left[\left(\frac{1}{\alpha}\right) \left(\ln\left(\frac{Max}{T_{res old}}\right) 1\right)\right] \left(\frac{\beta}{\alpha}\right)$
Where, $\alpha, \beta, \gamma, \omega, \theta$, and μ are regression parameters (α, γ, θ are intercepts and β, ω , and μ are slopes), t = elapsed time (year), and Max = maximum value of cracking			

2.6. Measures of Effectiveness

Several measures have been introduced to evaluate the short-term effectiveness of preventive maintenance activities, which include performance jump, deterioration reduction level, and deterioration rate reduction (Labi and Sinha 2003; Lu and Tolliver 2012). Long-term performance measures include the increase in pavement service life and cost-effectiveness of the preventive maintenance activities (Labi et al. 2004; Mamlouk and Dosa 2014; Rajagopal and George 1991).

2.6.1. Performance Jump

Performance jump is the immediate improvement in pavement conditions after performing the maintenance (Rajagopal and George 1991). It is considered as one of the most accurate measurements of short-term effectiveness as it avoids age-related complications of other time-delayed performance measures (Labi et al. 2004; Lytton 1987; Smith et al. 1993).

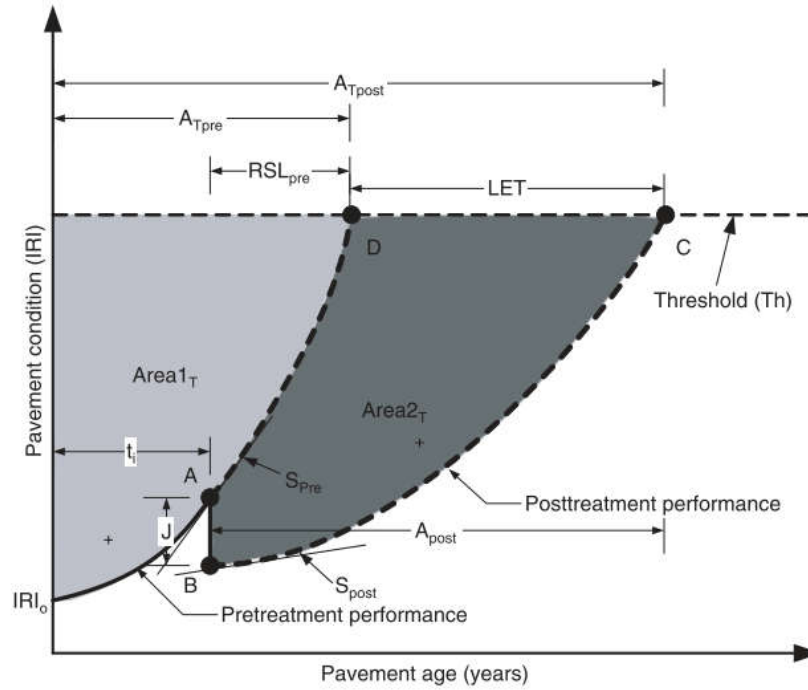


Figure 2.4. Treatment optimum timing: long-term modeling approach

Table 2.12. Summary of the performance prediction models

Indicator	Model	Reference
Pavement condition rating at time t (PCR(t))	$PCR(t) = 90$ $a \left\{ \exp \left(\frac{Age}{T} \right)^b - 1 \right\}$ $\times \log(ESALC) \left(\frac{BEFL}{SNC} \right)^c$	(Rajagopal and George 1991)
Pavement condition rating after treatment (PCRAF)	$PCRAF = A \times (PCRAF)^B \times T^C$	(Rajagopal and George 1991)
Probability of Failure (POF)	$POF_{dry\ freeze} = 1 - e^{-\left(\frac{Age}{10.92}\right)^{0.60}}$ $POF_{wet\ freeze} = 1 - e^{-\left(\frac{Age}{5.25}\right)^{0.89}}$ $POF_{wet\ non-freeze} = 1 - e^{-\left(\frac{Age}{15.69}\right)^{0.84}}$ $POF_{dry\ freeze} = 1 - e^{-\left(\frac{ESAL}{3.73}\right)^{2.57}}$ $POF_{wet\ freeze} = 1 - e^{-\left(\frac{ESAL}{2.93}\right)^{3.99}}$ $POF_{wet\ non-freeze} = 1 - e^{-\left(\frac{ESAL}{3.43}\right)^{4.79}}$	(Liu and Gharaibeh 2013)

(table cont'd.)

Indicator	Model	Reference
Skid Number (SN)	$SN = .3815 \text{ Age} + 59.4487$	(Romero and Anderson 2005)
Percent of mile with SN<40 (SN(%))	$SN(\%) = 1.9176 \text{ Age} - 1.2403$	(Romero and Anderson 2005)
Survival probability (S)	$S = \frac{0.027 \times \text{Life}^2 + 0.0179 \times \text{Life}}{+ 1}$	(Morian et al. 2011)
Pavement Condition Rating (PCR)	$PCR_{61 \text{ to } 65} = 7.2265 \text{ Age} + 92.666$ $PCR_{66 \text{ to } 70} = 4.7031 \text{ Age} + 93.059$ $PCR_{71 \text{ to } 75} = 4.6069 \text{ Age} + 94.745$ $PCR_{76 \text{ to } 80} = 4.0023 \text{ Age} + 94.229$ $PCR_{81 \text{ to } 85} = 4.9661 \text{ Age} + 95.511$ $PCR_{86 \text{ to } 90} = 3.9791 \text{ Age} + 95.873$	(Rajagopal 2010)
Mean Texture Depth (MTD) (in)	$MTD = 0.096 - 0.125 \text{ EAR}$	(Roque et al. 1991)
Texture depth in 1 year (Td1) (mm)	$Td1 = 0.07 \times \text{ALD} \times \log Yd + 0.9$	(Transit New Zealand (TNZ) 1981)
Pavement Condition Rating (PCR)	$PCR_{fair} = 88.058 - 1.3704 \times \text{Age}$ $PCR_{good} = 93.381 - 2.0178 \times \text{Age}$ $PCR_{all} = 90.082 - 1.6146 \times \text{Age}$	(Hein and Rao 2010)
Pavement Rating Score (PRS)	$PRS = 45.26 + 4.37 \text{ Age} + 9.79 \text{ IC} - 9.21 \text{ SA} + 10.43 \text{ SG}$	(Morian et al. 1998)
Pavement Condition Index (PCI)	$PCI = 10 \times (0.1 \times \text{RCI})^{0.5} \times \text{DMI} \times 0.962$	(Li and Kazmierowski 2004)
International Roughness Index (IRI) (in/mile)	$IRI = 3.97091 + 0.8932 \text{ Initial IRI} + 2.87797 \text{ Age} + 1.29244 \text{ Class}$	(Liu et al. 2009)
Rut Depth (RD) (in)	$RD = 0.03621 + 0.76501 \text{ Initial RD} - 0.00404 \text{ Class}$	
Equivalent number of full-width transverse cracks per 100 ft segment (TCR)	$TCR = 0.0765 + 0.7833 \text{ Initial TCR} + 0.0175 \text{ Age} + 0.0561 \text{ Class}$	
Equivalent fatigue cracks per 100 ft segment (FCR) (ft/100 ft)	$FCR = 0.24839 + 0.49664 \text{ Initial FCR} + 0.00008 \text{ ESAL} + 0.15381 \text{ Class}$	

A study by Haider and Dwaikat observed 5 to 10% performance jumps in IRI due to chip seal treatments. They also reported that the rate of deterioration after treatment was higher for chip seal treatments as compared to slurry seal, crack seal, and thin overlays as shown in Figure 2.5.

Labi and Sinha studied the effectiveness of seal coating for 35 pavement sections and observed that higher performance jumps are associated with the poor initial conditions of the pavement. Furthermore, the benefits of treatment activities applied to pavements with good to excellent initial conditions were negligible in terms of performance jumps (Labi et al. 2004).

After studying several intrinsically non-linear functional forms, the study presented a seal coating performance jump model, as shown in Figure 2.6. The model is as follows:

$$PJ = A \times \exp (IPC - B)^C \quad (2.1)$$

Where,

PJ = performance jump experienced by the pavement due to seal coating activity (PSI)

IPC = initial pavement condition at the time of maintenance (PSI)

A, B and C = constants

Another research by Labi et al. studied the performance jumps due to microsurfacing treatments in terms of initial surface roughness (IRI), rut depth (RUT) and pavement condition rating (PCR) (Labi et al. 2007). The study concluded a certain level of short-term benefits can be obtained by microsurfacing and pretreatment IRI, RUT and PCR are the most important predictors of performance jump in microsurfacing treatment. The observed correlations of performance jump with these performance indicators is presented in Figure 2.7.

However, other researchers have reported that performance jumps are not solely dependent upon the pre-treatment conditions of the pavement; they are significantly influenced by other endogenous and exogenous factors, such as traffic, age, type and class of the pavements (Madanat and Mishalani 1998).

Lu and Tolliver studied the relationships of performance jumps with pre-treatment IRI conditions for different levels of treatment types (Lu and Tolliver 2012). As can be seen from Figure 2.8, for lower level of treatments such as chip seal, aggregate seal and crack sealing there exists a maximum limit beyond which no treatment effectiveness can be obtained. However, for higher level of treatments such as mill and overlay, the effectiveness gain period exceeds the life of the pavement. The study found the following average reductions for different types of treatments: Hot mill overlay: 1.44 m/km IRI, Crack sealing: 0.27 m/km IRI, Aggregate sealing: 0.31 m/km IRI, Chip seal: 0.72 m/km IRI.

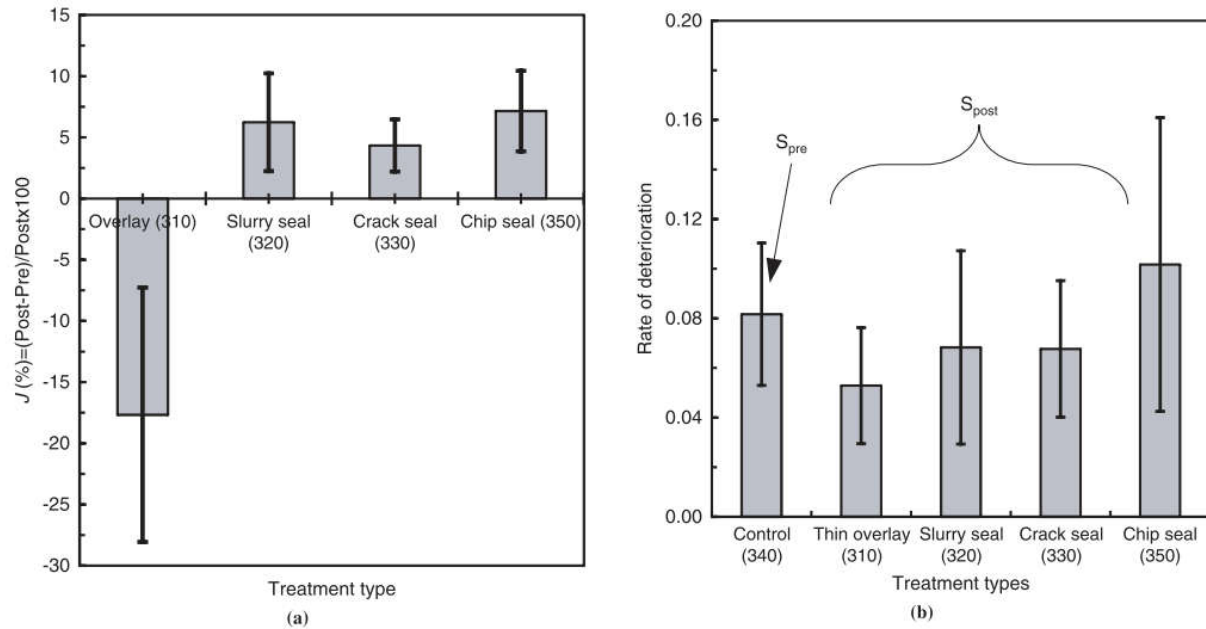


Figure 2.5. IRI jump and rate of deterioration comparison among different treatments (Haider and Dwaikat 2011)

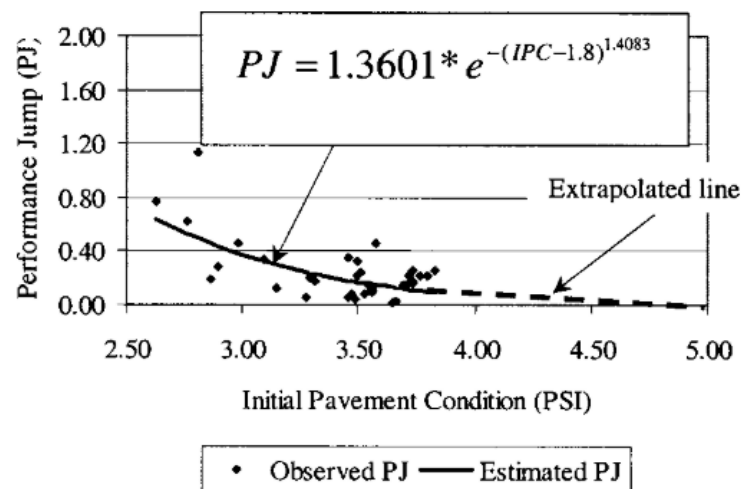


Figure 2.6. Non-linear Seal coating performance jump model (Labi et al. 2004)

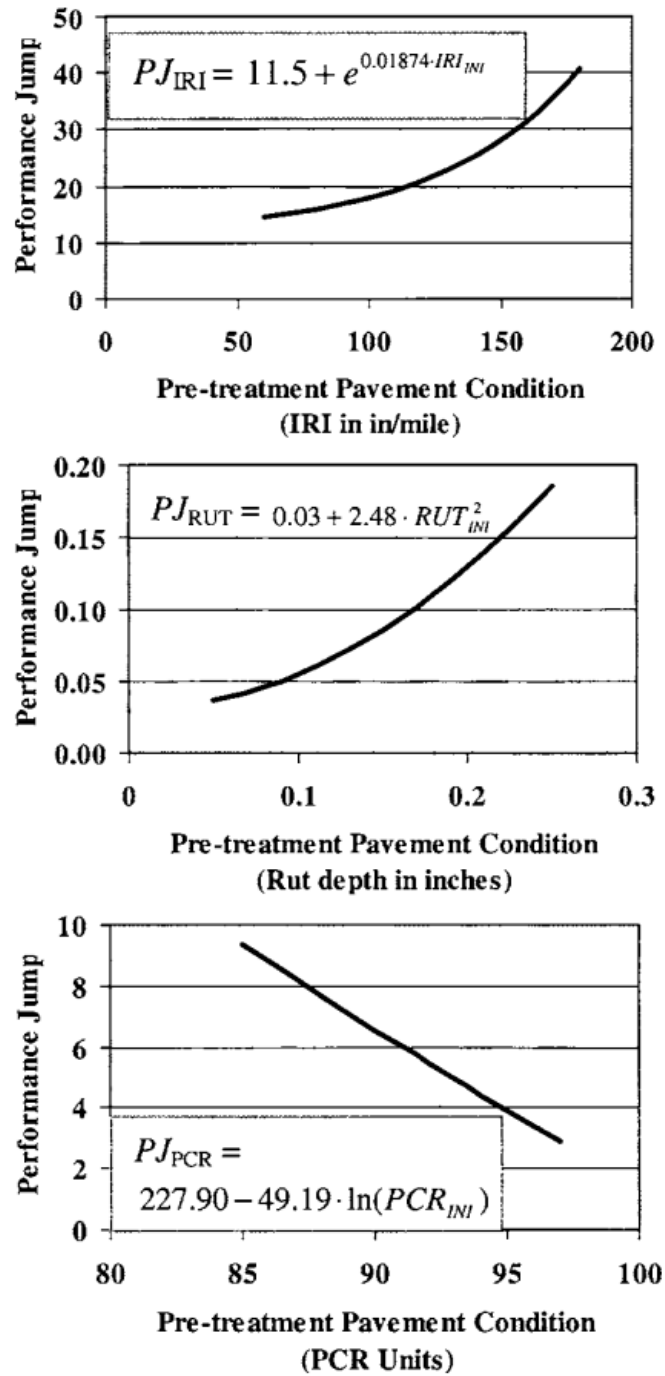


Figure 2.7. Microsurfacing performance jumps for different performance indicators (Labi et al. 2007)

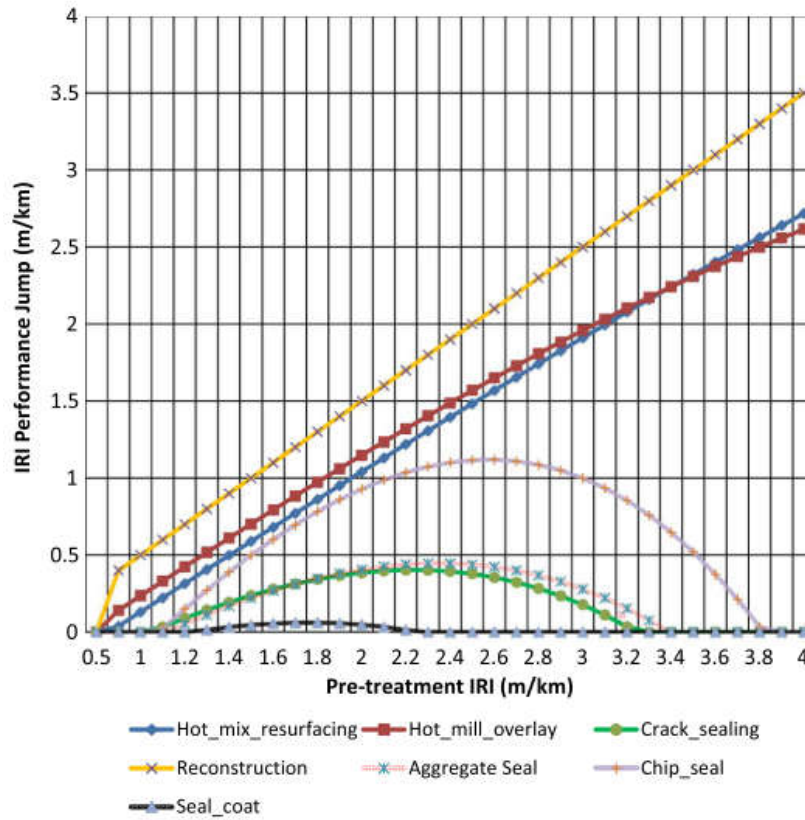


Figure 2.8. Relationship between performance jump and pretreatment IRI conditions for different treatments (Lu and Tolliver 2012)

2.6.2. Deterioration Rate Reduction

Deterioration rate reduction measures the slowing down of deteriorations of a pavement due to the application of a maintenance activity. Initial condition of the pavement and the type of applied treatment were found to be the most important factors influencing the deterioration reduction levels (Labi et al. 2004). The difference between the pretreatment and post-treatment performance curve slopes indicate the deterioration rate reduction levels (Lytton 1987). Smith et al. also described the same concept as ‘deterioration rate variation’ (Smith et al. 1993).

Labi et al. presented a non-linear deterioration rate reduction model for seal coating, see Figure 2.9. The model is as follows:

$$DRR = \exp \left[\frac{1}{C + A \times B^{IPC}} \right] \quad (2.2)$$

where,

DRR = deterioration rate reduction due to seal coating on flexible pavements (PSI)

IPC = initial pavement condition (PSI)

A, B and C = constants

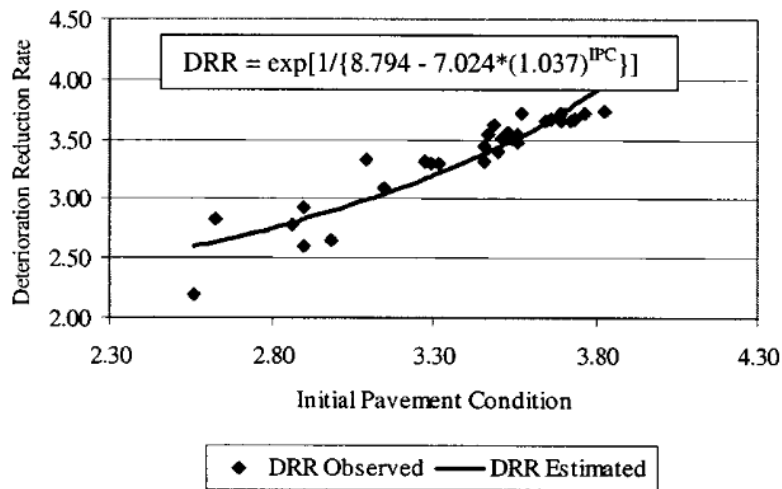


Figure 2.9. Non-linear Seal coating deterioration rate reduction model (Labi et al. 2004)

2.6.3. Service Life Extension

Ram and Peshkin studied the performance of Michigan DOT's preventive maintenance program and reported a service life extension of 4.3 to 6 years for single chip seal and 6.9 years for double chip seal applied on flexible pavements (Ram and Peshkin 2013). The study found that most of the preventive maintenance activities were performed on pavements in fair to good conditions. Microsurfacing and HMA mill and overlay treatments were found to be the most effective treatments in terms of increase in service life. Another study by Kiefer et al. reported an increase of 4.1 years in service life when chip seal was applied on flexible pavements; yet, chip seal treatments experienced a reduction in service life extension when it was used with fog seal (Kiefer et al. 2017). To verify the hypothesis that chip seal can be applied in a preventive mode, Mamlouk and Dosa evaluated the long-term effectiveness of this treatment based upon initial roughness conditions of the pavements under four different climatic conditions. The increase in service life for smooth, medium, and rough pavements due to chip seal treatments were found to be 4-7 years, 2-3 years and 0-1 years, respectively. The benefit-cost ratios obtained for this treatment ranged from 8 to 15 for smooth pavements, 3 to 4 for medium pavements and the ratio was insignificant for rough pavements. The study concluded that for chip seal to be effective, it must be applied on pavements before surface distresses become significant (Mamlouk and Dosa 2014).

Hall and Correa used long-term pavement performance (LTPP) data to evaluate the maintenance effectiveness of thin overlay, slurry seal, crack seal and chip seal for both rigid and flexible pavements (Hall et al. 2002). The study found that the same treatment may improve one pavement condition, such as random cracking, but it may have no or even a negative effect on other conditions, such as rutting and bleeding. Yet, most of the studies in the past have used a composite index to study the performance of maintenance activities (Labi et al. 2004; Ponniah and Kennepohl 1996; Rajagopal and George 1991). There remains a possibility of bias as a composite index computation involves all the pavement condition measures and some of which may not be affected or negatively affected by a specific type of treatment. Therefore, individual

pavement distresses in addition to a composite index were considered in the present study to evaluate the performance and cost-effectiveness of chip seal and microsurfacing.

2.7. Cost-Effectiveness of Treatment Activities

2.7.1. Cost-Benefit Analysis Methodologies

Several approaches have been used in the past to evaluate the cost-effectiveness of the treatment maintenance activities. Table 2.13 lists the most commonly used approaches in estimating the economic benefits of a maintenance treatment activity. Equivalent annual cost approach is the most straightforward one and life-cycle cost analysis approach is used for a more in-depth result.

Table 2.13. Common approaches used in cost-benefit analysis (Morian 2011)

Method	Input	Output
Life-Cycle Cost Analysis	<ul style="list-style-type: none"> • Interest rates • Inflation • Analysis period • Unit cost for treatment • Estimated life of treatment 	Present Value (PV) or Equivalent Uniform Annual Cost (EUAC) for each proposed treatment
Equivalent Annual Cost	<ul style="list-style-type: none"> • Unit cost for treatment • Estimated life of treatment 	Unit performance life of treatment per cost
Cost-Effectiveness Analysis	<ul style="list-style-type: none"> • Pavement performance curve 	Area under the pavement performance curve is equivalent to effectiveness
Longevity Cost Index	<ul style="list-style-type: none"> • Treatment unit cost • Present value of unit cost over life of treatment • Traffic loading • Life of treatment 	Relates present value of cost of treatment to life and traffic

Life-Cycle Cost Analysis

Hicks et al defined life cycle costs as “an economic assessment of an item, system, or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars (Hicks et al. 1999).” The highway maintenance agencies use this tool to comprehensively assess the long-term costs associated with a proposed treatment activity, compare among several feasible treatments and allocate the funds optimally.

Maintenance Treatment Cost Effectiveness

To assess the cost-benefits of chip seal, a cost-effectiveness analysis was conducted. The performance of chip seal applied at a level before reaching the threshold was compared with the performance of the existing pavement without any maintenance activity, i.e., with the ‘do

nothing' baseline performance model. The following equations were used to estimate the equivalent uniform annual costs (EUAC) for the different cases (Morian 2011):

$$EUAC_{do\ nothing} = IC \times \left[\frac{(1+i)^{SL_{pre}}}{(1+i)^{SL_{pre}-1}} \right] \quad (2.3)$$

$$NPV_{treatment} = IC + PMC_{t_i} \times \frac{1}{(1+i)^{t_i}} \quad (2.4)$$

$$EUAC_{treatment} = NPV_{treatment} \times \left[\frac{(1+i)^{SL_{post}}}{(1+i)^{SL_{post}-1}} \right] \quad (2.5)$$

$$NPV_{ST} = PMC_{t_i} \times \frac{1}{(1+i)^{t_i}} \quad (2.6)$$

$$EUAC_{ST} = NPV_{ST} \times \left[\frac{(1+i)^{SL_{post}}}{(1+i)^{SL_{post}-1}} \right] \quad (2.7)$$

where,

IC = initial cost,

i = discount rate,

t_i = year of expenditure,

PMC_{t_i} = surface treatment cost at year t_i ,

SL_{pre} = service life without treatment, and

SL_{post} = service life with treatment.

The benefit of the treatment activities was determined as the monetary savings due to the treatment activity:

$$EUAC = EUAC_{do\ nothing} - EUAC_{treatment} \quad (2.8)$$

The benefit-cost ratios for the projects are given by the following equation:

$$\frac{B}{C} = \frac{EUAC}{EUAC_{ST}} \quad (2.9)$$

where,

$EUAC$ = monetary savings due to the treatment activity, and

$EUAC_{ST}$ = equivalent uniform annual costs for the surface treatment activity.

2.7.2. Past Studies on Cost-Effectiveness of Chip seal and Microsurfacing

Ram et al. studied the cost-effectiveness of Michigan DOT's preventive maintenance program by evaluating the pavement service life extension, benefit area and benefit-cost ratios of the associated projects (Ram and Peshkin 2013). HMA crack seals were found to have the highest benefit-cost ratios for the flexible pavements, whereas microsurfacing was found to be the most cost-effective for composite pavements followed by crack seals and double chip seals. The benefit-cost ratios ranged from 0.11-0.48 for single and double chip seal and 0.09-0.26 for double microsurfacing. However, the study concluded that only a single measure like cost-effectiveness should not be used as the sole parameter in selecting the appropriate maintenance treatment activity. The study also used a simplified life cycle cost analysis approach to compare the benefits accrued from a CPM strategy and a rehabilitation only strategy. The results indicated that a rehabilitation only strategy generated an average benefit of almost \$265,000 per

lane-mile for composite pavements and on the other hand, MDOT's CPM program for flexible pavements resulted in an average savings of almost \$310,000 per lane-mile.

Tarefder et al. evaluated the cost-effectiveness of millings over virgin chips in terms of benefit area, EUAC, B-C ratio, and Effectiveness Index (Tarefder and Ahmad 2016). For all the cases chip seals with milling were found to have better economic benefits than chip seals without millings. The benefit-cost ratios for the sections with chip seals with virgin chips ranged from 0.51 to 0.89 whereas the benefits cost ratios for the projects with millings ranged from 0.66-1.35. Other measures also indicated similar outcomes.

Another study by Mamlouk et al. calculated the benefit-cost ratios based on the surface conditions of the chip seals applied in four different climatic zones of the United States (Mamlouk and Dosa 2014). The results show that the smooth pavements have the highest benefit-cost ratios across all four climatic zones, and B-C ratios for these pavements ranged from 8 to 15. The results further indicate that the chip seals are more cost-effective in dry freeze and wet non-freeze zone as compared to the wet-freeze and dry no-freeze zones.

Pennsylvania Department of Transportation conducted a study to assess the benefits and costs associated with microsurfacing and other similar tools in pavement treatment strategies (Morian 2011). The study discussed several approaches in assessing the economic aspects of these treatment activities and reported that the approaches may result in slight differences in the outcomes, but the relative ranking of the treatments remain the same. Statewide surveys indicated that typical cost for microsurfacing and chip seal ranged from \$2-4/SY and \$1-2/SY respectively. The study also identified several other potential cost-effective treatments and compared the equivalent annual cost (EAC) of these treatments with respect to the EAC's of thin overlays. The findings have been summarized in Table 2.14. Another study by Hicks et al. has also reported similar unit costs and expected life of the treated pavements as shown in Table 2.15.

Rajagopal evaluated the cost-effectiveness of 225 chip seal and 214 microsurfacing projects (Rajagopal 2010). The study found that on average chip seals are economically beneficial than the microsurfacing treatments when compared to the costs of thin AC. The treatments were also found more beneficial when applied to the pavements having a prior PCI of 71-75. The results are shown in Figure 2.10.

Table 2.14. EAC based on the survey of state highway agencies (Morian 2011)

Treatment type	Cost (\$/yd ²)		Performance life (year)		EAC (\$/yd ² /year)			Cost ratio
	Low	High	Max	Min	Low	High	Ave	
Thin Overlay	2.55	5.50	12	7	0.21	0.79	0.50	1.00
Microsurfacing	2.00	4.00	12	5	0.17	0.80	0.48	0.97
Crack Sealing	0.32	0.40	5	2	0.06	0.20	0.13	0.26
Chip Seal	0.90	1.78	8	4	0.11	0.45	0.28	0.56
NovaChip®	4.50	6.50	15	8	0.30	0.81	0.56	1.11
Fog Seal	0.25	0.60	5	2	0.05	0.30	0.18	0.35
Slurry Seal	1.50	3.00	6	4	0.25	0.75	0.50	1.00

Watson and Jared evaluated Georgia DOT's experience with microsurfacing as an economical alternative to conventional dense-graded resurfacing (Watson and Jared 1998). The

study estimated about 5 to 7 years increase in service life for the southeastern region of the US, where the cost of microsurfacing mix ranged from \$1.07 to \$1.20/m². Hixon and Ooten showed that the initial cost of microsurfacing is 55% of an overlay; yet, the annual cost of microsurfacing was found to be slightly higher than an asphalt concrete overlay (Hixon and Ooten 1993). Most of the past research pertaining to microsurfacing has mainly focused on the general effectiveness of the treatment and did not take into account exogenous factors such as special geographical and climatological issues. In addition, past studies did not evaluate the effects of microsurfacing on moisture damage.

Table 2.15. Typical unit costs and expected life of the preventive maintenance treatments (Hicks et al. 1999)

Treatment	Cost/m ²	Cost/yd ²	Expected life of treatment		
			Min.	Average	Max
Crack Treatment	\$0.60	\$0.50	2	3	5
Fog Seals	\$0.54	\$0.45	2	3	4
Slurry Seals	\$1.08	\$0.90	3	5	7
Microsurfacing	\$1.50	\$1.25	3	7	9
Chip Seals	\$1.02	\$0.85	3	5	7
Thin Hot-Mix Overlay	\$2.09	\$1.75	2	7	12
Thin Cold-Mix Overlay	\$1.50	\$1.25	2	5	10

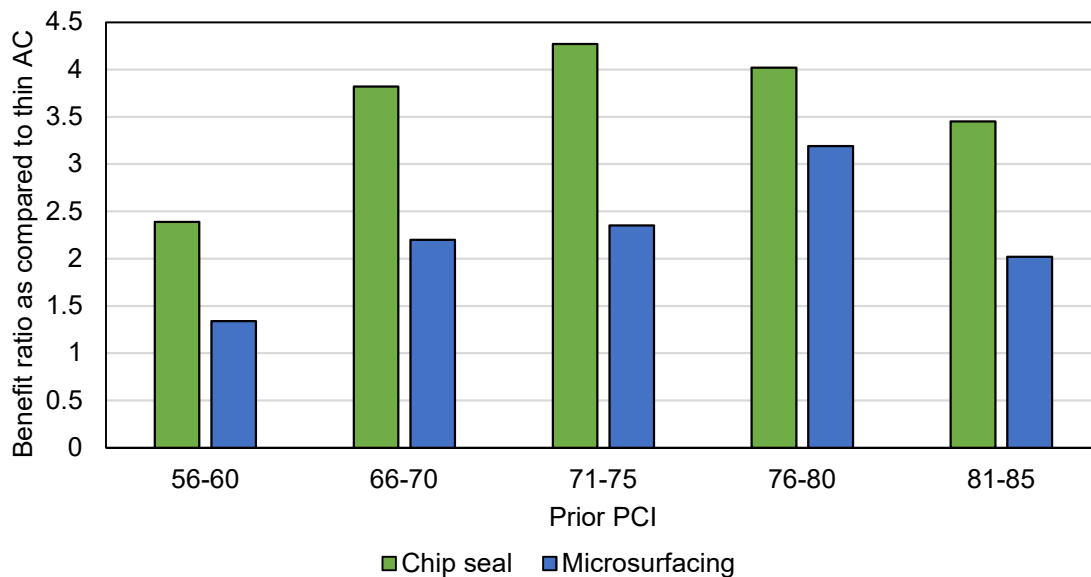


Figure 2.10. Relative benefit ratios for chip seal and microsurfacing (Rajagopal 2010)

CHAPTER 3. METHODOLOGY

Flexible pavements with chip seal, and microsurfacing treatment that satisfy other project acceptance criteria, detailed subsequently, were selected for a detailed performance and economic evaluation. Performance curves for each of sections were developed by modeling pavement conditions as a function of time. Long-term pavement performance data were used to quantify the benefits of microsurfacing treatments in terms of pavement performance indicators. The research approach of this study is illustrated in Figure 3.1.

3.1. Pavement Performance Indicators

Louisiana pavement management system monitors roughness, rutting, and cracking (alligator, random, transverse, and longitudinal), which are the critical performance indicators in terms of safety, ride quality, and overall conditions of the pavement. However, all the indicators are not equally important for different treatment types. Therefore, in selecting the most appropriate indices for a treatment effectiveness evaluation, it is vital to consider the type and the existing conditions of the pavement along with the method of evaluating the performance of the treatment (Labi et al. 2006).

Chip seal is typically applied to address random cracks, low severity fatigue cracks, and raveling. Random cracking index, roughness index, and composite index can assess the changes of severity and extent of these distresses over the years more accurately and therefore these three indices have been considered as the performance indicators of chip seal treatments.

- Random Cracking Index (RCI): A measure of all cracking, longitudinal and transverse, found outside the 36-inch wheelpath on asphalt pavements.
- Roughness Index (RFI): A measure of the longitudinal irregularities in the pavement surface;
- Pavement Condition Index (PCI): represents the overall conditions of the pavement.

Microsurfacing is typically applied to treat rutting, roughness, and surface irregularities. Indices that reflect the changes in extent and severity of these distresses would be the ideal performance indicators for microsurfacing. Therefore, to investigate the effectiveness of microsurfacing treatments, the following performance indicators were used in this study:

- Rutting Index (RTI): A measure of the average longitudinal depressions in the pavement wheel paths;
- Roughness Index (RFI): A measure of the longitudinal irregularities in the pavement surface;
- Pavement Condition Index (PCI): represents the overall conditions of the pavement.

All the indices are measured on a scale that ranges from 0 to 100, where 100 represents the best possible condition.

3.2. Pavement Performance as a Function of Time

Several studies have used a polynomial approach to model pavement conditions (Khattak et al. 2009; Lu and Tolliver 2012; Morian 2011). In this study, it was assumed that both pre and post-treatment conditions could be represented by polynomial models as depicted in Equations (3.1) and (3.2); see Figure 3.2:

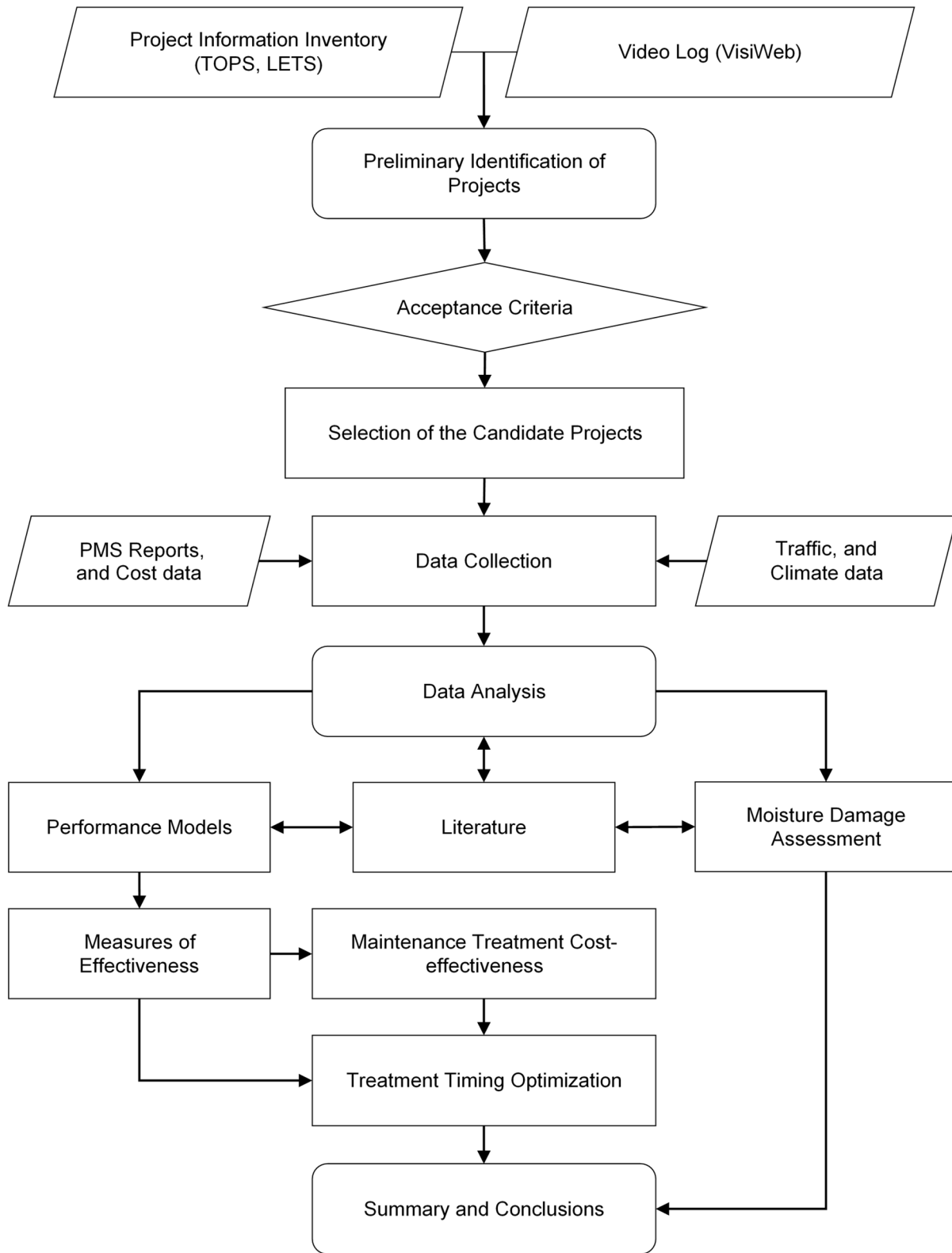


Figure 3.1. Outline of the research approach

$$f_{pre}(t) = a_1 t^2 + b_1 t + c_1 \quad (3.1)$$

$$f_{post}(t) = a_2 t^2 + b_2 t + c_2 \quad (3.2)$$

where,

a_1, b_1, c_1, a_2, b_2 and c_2 = fitting parameters related to pavement conditions and deterioration rates over time for pre and post-treatment performance models; and

t = Time in years.

According to the model, the conditions of a pavement will deteriorate over time following curve A-C as shown in Figure 3.2; however, if any treatment is applied at time t_i (point B), the pavement condition index will increase to point D. This immediate increase in pavement condition index following a treatment activity is known as a performance jump. After the jump, the deterioration pattern will follow the curve DE. The time is set equal to zero at point D for the post-treatment performance curve.

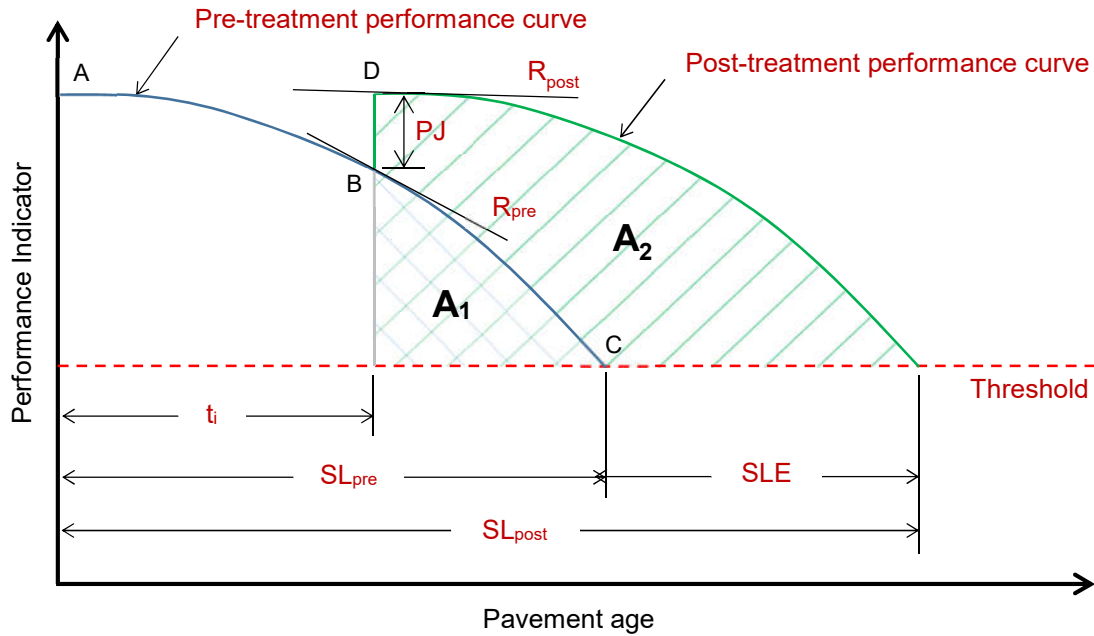


Figure 3.2. Pre and post-treatment performance curves due to microsurfacing application

3.3. Measures of Effectiveness

The initial effects, if any, of chip seal and microsurfacing on random cracking, roughness, rutting, and overall conditions of the pavement were evaluated in terms of performance jump and deterioration rate reduction. Long-term effects of the treatment were evaluated in terms of effectiveness and service life extension.

3.3.1. Performance Jump (PJ)

Performance jump is the immediate improvement in pavement conditions after applying the surface treatment (Rajagopal and George 1991). Pavement conditions just before and after the treatment can be estimated as follows:

$$f_{pre}(t_i) = a_1 t_i^2 + b_1 t_i + c_1 \quad (3.3)$$

$$f_{post}(0) = c_2 \quad (3.4)$$

PJ was calculated by subtracting Equation (3.3) from Equation (3.4) as follows:

$$PJ = c_2 - (a_1 t_i^2 + b_1 t_i + c_1) \quad (3.5)$$

3.3.2. Deterioration Rate Reduction (DRR)

DRR refers to the slowing down of the pavement deterioration, which can be estimated as the difference in the slope between before and after treatment curves as follows (Haider and Dwaikat 2011):

$$R_{pre} = \left. \frac{df_{pre}(t)}{dt} \right|_{t=t_i} = 2a_1 t_i + b_1 \quad (3.6)$$

$$R_{post} = \left. \frac{df_{post}(t)}{dt} \right|_{t=0} = b_2 \quad (3.7)$$

$$DRR = \frac{R_{post}}{R_{pre}} \quad (3.8)$$

where,

R_{pre} and R_{post} = rate of deterioration just before and after the treatment.

3.3.3. Effectiveness (E)

Effectiveness is defined as the increase in average pavement conditions over the long-term due to chip seal and microsurfacing (Labi et al. 2006). For a treated section, the average pavement conditions over the service life, P_{AVG} , can be obtained as follows:

$$P_{AVG} = \frac{1}{n_c} (y_1 + y_2 + \dots + y_n) \quad (3.9)$$

where,

y_1 = Pavement condition after treatment;

y_2, y_3, \dots, y_{n-1} = Pavement condition at different years after treatment;

y_c = Pavement condition at the end of service life after treatment; and

n_c = Number of years the pavement condition was measured after treatment.

Effectiveness is the percentage change in average pavement conditions due to chip seal or microsurfacing relative to the pretreatment conditions of the pavement.

$$E = \left(\frac{P_{AVG} - P_{INI}}{P_{INI}} \right) \times 100 \quad (3.10)$$

where,

P_{INI} = Pre-treatment condition of the pavement in terms of performance indicators.

3.3.4. Service Life Extension (SLE)

The pre and post-treatment performance curves will reach the threshold at different times, which can be estimated using Equations (11) and (12):

$$SL_{pre} = \frac{-b_1 - \sqrt{-b_1^2 - 4a_1(c_1 - TV)}}{2a_1} \quad (3.11)$$

$$SL_{post} = \frac{-b_2 - \sqrt{-b_2^2 - 4a_2(c_2 - TV)}}{2a_2} + t_i \quad (3.12)$$

where,

SL_{pre} = Pavement age with no treatment to the threshold;

SL_{post} = Pavement age with treatment to the threshold;

TV = Threshold value for pavement condition index; and

t_i = Time of the treatment activity in years.

SLE is given by the difference between pre and post-treatment service lives:

$$SLE = SL_{post} - SL_{pre} \quad (3.13)$$

where,

SLE = Service life extension in years.

3.3.5. Treatment Cost-effectiveness

The CE of a treatment is defined as the ratio of treatment net benefits (TNB) to the unit cost of the treatment (Peshkin et al. 2004). It is estimated as follows:

$$CE = \frac{TNB}{\text{Unit cost of the treatment (\$/mile)}} \quad (3.14)$$

TNB is calculated as the increased area under the performance curve due to the treatment activity. According to Figure 3.2, TNB can be expressed as:

$$TNB = A_2 - A_1 \quad (3.15)$$

$$A_2 = \int_0^{SL_{post} - t_i} (f_{post} - TV) dt$$

$$\therefore A_2 = \frac{a_2}{3} (SL_{post} - t_i)^3 + \frac{b_2}{2} (SL_{post} - t_i)^2 + (c_2 - TV)(SL_{post} - t_i) \quad (3.16)$$

$$A_1 = \int_{t_i}^{SL_{pre}} (f_{pre} - TV) dt$$

$$\therefore A_1 = \frac{a_1}{3} (SL_{pre} - t_i^3) + \frac{b_1}{2} (SL_{pre}^2 - t_i^2) + (c_1 - TV)(SL_{pre} - t_i) \quad (3.17)$$

where,

A_2 = Area enclosed between post-treatment performance curve and threshold value;

A_1 = Area enclosed between pre-treatment performance curve and threshold value.

CHAPTER 4. DATA COLLECTION

Louisiana DOTD (LaDOTD) databases including Pavement Management System (PMS), Highway Needs, Tracking of Projects (TOPS), Material Testing System (MATT), letting of projects (LETS) and Project and Highway Information inventory were analyzed to collect the data required for a detailed performance evaluation and economic analysis.

4.1. Selection of Candidate Projects

A preliminary list of microsurfacing projects was prepared using the Tracking of Projects (TOPS) and Letting schedule (LETS) databases. To determine the exact location, length, and the date of the treatment application, video logs were reviewed using the VisiWeb (iVision) software. The user interface of the software is shown in Figure 4.1. This software offers geocoded videos of the pavements along with other relevant characteristics of the pavements, such as cracking pattern, roughness, and elevation.

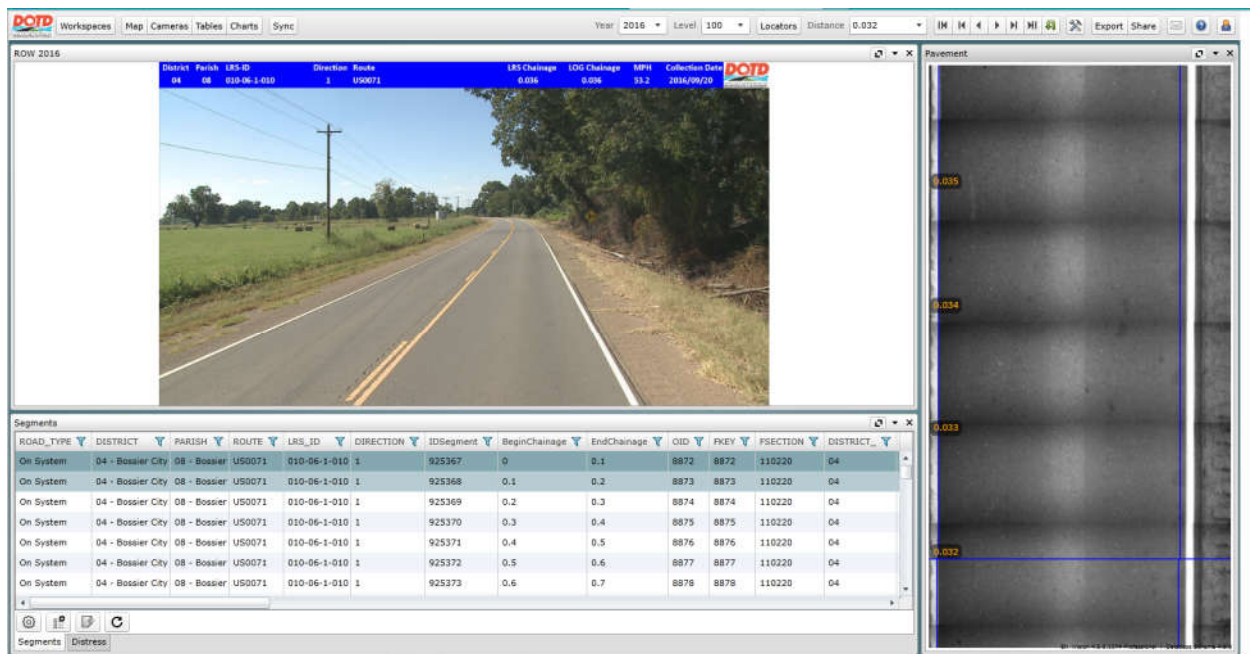


Figure 4.1. User interface of the iVision software

To facilitate quantification of treatment effectiveness and plotting of the pavement performance model, a candidate project had to meet the following project acceptance criteria:

- A road segment should have pavement condition data available for a minimum of four cycles before and four cycles after the application of chip seal and microsurfacing so that non-linear models can be fitted through the data points.
- Distress data should follow a decreasing pattern over the years except for the year after treatment, which should exhibit an increase in the distress index value.

The earliest distress data available in LaDOTD database were collected in 1995, and since then the distress data have been collected every two years (Khattak et al. 2008). A total of ten sets of data is available, and the latest available data set was recorded in 2015. As the

candidate projects should have at least four data points before and four data points after the treatment, sections receiving treatments in-between 2003 and 2010 were found to be suitable for the performance analysis. However, fewer sections were found to conform to the second criteria, as it is very uncommon for a section not to receive any treatment or maintenance activity other than chip seal and microsurfacing during a long period of time. Table 4.1 and 4.2 describes the projects selected for analysis. The locations of these projects have been illustrated in Figure 4.2.

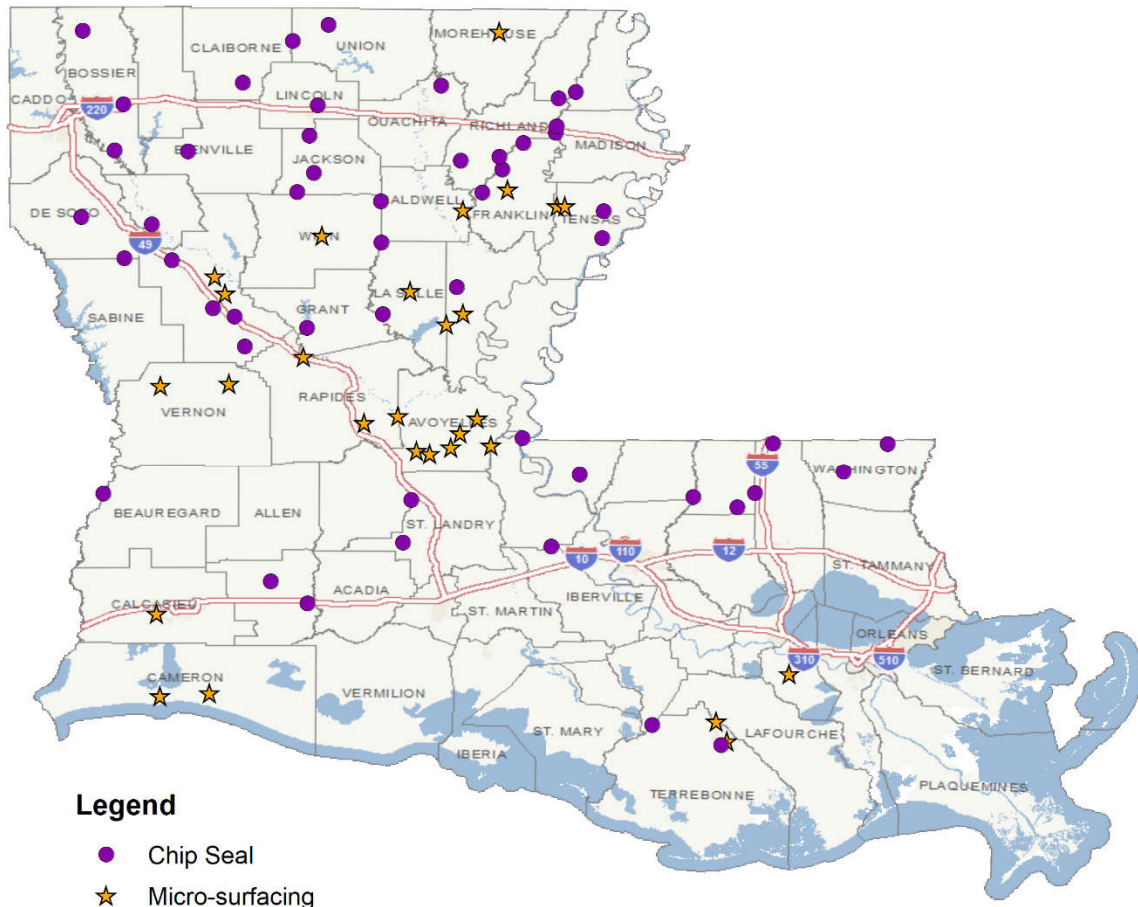


Figure 4.2. Location of the projects selected for analysis

To achieve a higher degree of accuracy in evaluating the effectiveness of microsurfacing application, each 0.1 mile of the section was used as a data point instead of using an average value for the whole section. Table 4.3 summarizes the total number of sections and log miles identified for the analysis. Performance curves were developed for each of the data points and a threshold values depending upon the road classification were used in the analysis. All the selected sections had a terminal threshold value ranging from 50 to 64. For consistency of the analysis, a threshold value of 60 was assumed in all the calculations.

Table 4.1. Summary of chip seal projects selected for analysis

ID	Control Section	Route	District	Parish	Pavement Type	Treatment	Date of Treatment	Project Limits		ADT
								BLM	ELM	
CS1	010-06	US 71	4	8	Asphalt	A7-Asph Surf Treat	8/28/2009	0.27	8.17	9900
CS2	020-30	LA 605	58	54	Asphalt	A7-Asph Surf Treat	10/14/2009	3.6	10.68	1740
CS3	021-03	US 84	4	16	Asphalt	A7-Asph Surf Treat	6/3/2009	2.3	12.27	4200
CS4	028-02	US 190	7	6	Asphalt	A7-Asph Surf Treat	10/6/2009	0	9.9	3200
CS5	035-03	LA 175	4	16	Asphalt	A7-Asph Surf Treat	9/12/2008	0	7.66	870
CS6	039-03	LA 8	58	13	Asphalt	A7-Asph Surf Treat	10/14/2009	0	9.32	1560
CS7	040-01	LA 8	8	22	Asphalt	A7-Asph Surf Treat	11/20/2006	3.74	11.24	1430
CS8	040-04	LA 8	58	30	Asphalt	A7-Asph Surf Treat	10/14/2009	0	4.56	2800
CS9	051-04	LA 17	5	42	Asphalt	A7-Asph Surf Treat	9/16/2009	0	2.38	6300
CS10	051-05	LA 17	5	42	Asphalt	A7-Asph Surf Treat	11/21/2008	0.75	9.04	3400
CS11	051-06	LA 17	5	62	Asphalt	A7-Asph Surf Treat	11/21/2008	0	8.39	2600
CS12	053-04	LA 1	8	35	Asphalt	A7-Asph Surf Treat	12/12/2008	0.07	3.72	2100
CS13	053-07	US 84	4	41	Asphalt	A7-Asph Surf Treat	9/12/2008	4	8.1	8700
CS14	069-01	LA 33	5	31	Asphalt	A7-Asph Surf Treat	8/8/2008	3.39	13.67	14000
CS15	082-04	LA 157	4	8	Asphalt	A7-Asph Surf Treat	9/12/2008	0	5.63	3400
CS16	083-04	LA 2	4	8	Asphalt	A7-Asph Surf Treat	9/12/2008	0.9	6.36	1870
CS17	083-11	LA 2-A	5	56	Asphalt	A7-Asph Surf Treat	12/7/2009	0	4.39	770
CS18	091-09	LA 126	58	11	Asphalt	A7-Asph Surf Treat	10/14/2009	0	12.77	560
CS19	115-02	LA 485	8	35	Asphalt	A7-Asph Surf Treat	7/2/2009	0.46	1.67	360
CS20	116-04	LA 478	8	35	Asphalt	A7-Asph Surf Treat	7/2/2009	3.35	4.14	130
CS21	118-03	LA 119	8	35	Asphalt	A7-Asph Surf Treat	7/2/2009	7.38	7.92	300
CS22	125-02	LA 124	58	30	Asphalt	A7-Asph Surf Treat	10/14/2009	0	3.63	1370
CS23	154-03	LA 15	5	56	Asphalt	A7-Asph Surf Treat	8/8/2008	0	6.31	750
CS24	161-08	LA 134	5	18	Asphalt	A7-Asph Surf Treat	2/22/2008	0	10.87	760
CS25	165-05	LA 135	58	21	Asphalt	A7-Asph Surf Treat	10/14/2009	0	3.42	580
CS26	168-01	LA 857	58	21	Asphalt	A7-Asph Surf Treat	10/14/2009	0	10.66	1890
CS27	168-02	LA 132	58	21	Asphalt	A7-Asph Surf Treat	10/14/2009	0	9.17	440

(table cont'd.)

ID	Control Section	Route	District	Parish	Pavement Type	Treatment	Date of Treatment	Project Limits		ADT
								BLM	ELM	
CS28	177-03	LA 15	58	15	Asphalt	A7-Asph Surf Treat	10/14/2009	0	17.27	420
CS29	199-02	LA 102	7	27	Asphalt	A7-Asph Surf Treat	7/21/2009	0	10.32	1380
CS30	251-01	LA 66	61	63	Asphalt	A7-Asph Surf Treat	11/10/2005	0	7.87	1630
CS31	259-01	LA 63	61	19	Asphalt	A7-Asph Surf Treat	8/7/2008	0	13.31	1600
CS32	270-05	LA 43	62	46	Asphalt	A7-Asph Surf Treat	9/23/2008	0	5.95	870
CS33	274-01	LA 436	62	59	Asphalt	A7-Asph Surf Treat	9/23/2008	0	10.25	2100
CS34	274-03	LA 438	62	59	Asphalt	A7-Asph Surf Treat	9/23/2008	0	8.79	840
CS35	293-02	LA 792	4	7	Asphalt	A7-Asph Surf Treat	7/24/2008	0	6.6	620
CS36	295-03	LA 518	4	14	Asphalt	A7-Asph Surf Treat	7/24/2008	0	4.24	410
CS37	316-02	LA 148	5	25	Asphalt	A7-Asph Surf Treat	11/2/2009	0	7.13	270
CS38	321-04	LA 505	5	25	Asphalt	A7-Asph Surf Treat	12/7/2009	0	5.22	750
CS39	348-02	LA 132	58	21	Asphalt	A7-Asph Surf Treat	10/14/2009	0	2.89	660
CS40	351-01	LA 575	58	54	Asphalt	A7-Asph Surf Treat	7/8/2008	0	8.9	250
CS41	380-02	LA 363	3	49	Asphalt	A7-Asph Surf Treat	1/22/2009	0	3.87	930
CS42	424-07	US 90	2	55	Asphalt	A7-Asph Surf Treat	6/24/2004	1	0	22300
CS43	825-09	LA 811	5	25	Asphalt	A7-Asph Surf Treat	11/2/2009	5.6	8.6	880
CS44	827-03	LA 102	7	27	Asphalt	A7-Asph Surf Treat	7/21/2009	0.82	8.04	1020
CS45	837-15	LA 134	5	37	Asphalt	A7-Asph Surf Treat	9/16/2009	0	5.97	1050
CS46	839-18	LA 977	61	39	Asphalt	A7-Asph Surf Treat	11/24/2008	0	4.35	1340
CS47	842-13	LA 132	5	42	Asphalt	A7-Asph Surf Treat	11/12/2009	0	2.13	400
CS48	846-08	LA 1047	62	46	Asphalt	A7-Asph Surf Treat	9/23/2008	0.85	4.2	300
CS49	849-03	LA 103	3	49	Asphalt	A7-Asph Surf Treat	1/22/2009	0	4.59	1160
CS50	853-01	LA 1055	62	53	Asphalt	A7-Asph Surf Treat	9/23/2008	3.87	8.73	1130
CS51	855-18	LA 3197	2	55	Asphalt	A7-Asph Surf Treat	5/16/2003	0	0.4	850

Table 4.2. Summary of the microsurfacing projects selected for analysis

ID	Control Section	Route	District	Parish	Pavement Type	Treatment	Date of Treatment	Project Limits		ADT
								BLM	ELM	
MS1	022-05	US 84	58	30	Asphalt	M3-Micro Surfacing	7/10/2009	9.96	13.7	2800
MS2	022-06	US 84	58	13	Asphalt	M3-Micro Surfacing	7/10/2009	0	10.49	6700
MS3	034-06	LA 6	8	35	Asphalt	M3-Micro Surfacing	6/30/2010	4.35	7.55	4800
MS4	036-02	LA 4	58	21	Asphalt	M3-Micro Surfacing	8/19/2009	0.55	2.09	770
MS5	036-04	LA 4	58	21	Asphalt	M3-Micro Surfacing	8/19/2009	9.64	12.75	1300
MS6	036-05	LA 4	58	54	Asphalt	M3-Micro Surfacing	8/19/2009	0.45	2.32	530
MS7	052-05	LA 1	8	5	Asphalt	M3-Micro Surfacing	10/6/2006	1.92	9.58	3800
MS8	052-08	LA 1	8	40	Asphalt	M3-Micro Surfacing	6/30/2010	0	7.34	2500
MS9	052-30	LA 1	8	5	Asphalt	M3-Micro Surfacing	12/3/2008	0	7.32	6100
MS10	053-02	LA 1	8	40	Asphalt	M3-Micro Surfacing	10/6/2006	3.28	8.86	1000
MS11	065-30	LA 3040	2	55	Asphalt	M3-Micro Surfacing	5/1/2002	3.69	6.34	40800
MS12	073-04	LA 457	8	40	Asphalt	M3-Micro Surfacing	7/16/2003	0.09	5.33	670
MS13	074-04	LA 28	58	13	Asphalt	M3-Micro Surfacing	7/10/2009	0	3.28	3400
MS14	126-01	LA 499	8	64	Asphalt	M3-Micro Surfacing	7/16/2003	0	6	1080
MS15	133-03	LA 111	8	58	Asphalt	M3-Micro Surfacing	7/16/2003	4.5	8.75	460
MS16	134-02	LA 8	8	58	Asphalt	M3-Micro Surfacing	10/6/2006	0	0.97	1260
MS17	146-01	LA 29	8	5	Asphalt	M3-Micro Surfacing	10/6/2006	2.02	7.86	3800
MS18	147-04	LA 107	8	5	Asphalt	M3-Micro Surfacing	10/6/2006	5.95	6.3	3000
MS19	172-30	LA 140	5	34	Asphalt	M3-Micro Surfacing	11/19/2003	0.04	3.62	640
MS20	173-01	LA 4	58	54	Asphalt	M3-Micro Surfacing	8/19/2009	0	13.12	2400
MS21	193-01	LA 27	7	12	Asphalt	M3-Micro Surfacing	7/26/2010	0	15.35	1620
MS22	193-02	LA 27	7	12	Asphalt	M3-Micro Surfacing	7/26/2010	0	8.49	2600
MS23	374-03	LA 451	8	5	Asphalt	M3-Micro Surfacing	7/16/2003	0	4	510
MS24	424-08	US 90	2	29	Asphalt	M3-Micro Surfacing	2/28/2002	7.36	11.83	30700
MS25	428-03	LA 3127	2	45	Asphalt	M3-Micro Surfacing	10/25/2007	2.91	10.13	14100
MS26	805-22	LA 362	8	5	Asphalt	M3-Micro Surfacing	10/6/2006	4.82	5	1905
MS27	810-27	LA 27	7	10	Asphalt	M3-Micro Surfacing	7/26/2010	0	2.06	19500
MS28	835-06	LA 494	8	35	Asphalt	M3-Micro Surfacing	7/16/2003	4.03	6.33	20400

Table 4.3. Size and description of the data sets used in the analysis

Treatment	Dataset ID	Analysis	Index	Number of sections	Number of log miles
Chip seal	I	Field performance	PCI	47	316
			RCI	39	379
			RFI	42	334
	II	Moisture damage	PCI	66	84 ¹
Microsurfacing	III	Field performance	PCI	25	322
			RTI	27	324
			RFI	27	360
	IV	Moisture damage	PCI	21	25 ¹
¹ Number of cores					

4.2. Distress Data

The pavement condition data, such as cracking, roughness, patching and rutting measurements are collected biennially using the Automated Road Analyzer (ARAN[®]) and the results are reported every 0.1 mile. For flexible and composite pavements, the random cracking index encompasses all random cracks, which include thermal transverse, reflective transverse, longitudinal, block, and cement-treated reflective cracks. The equations used to calculate random cracking index (RCI), the roughness index (RFI), and the rutting index (RTI) are as follows (LaDOTD 2018):

$$RCI = MIN\{100, MAX(0, 100 - DP_L - DP_M - DP_H)\} \quad (4.1)$$

where,

DP = deduct point due to random cracks; and subscripts L, M, and H refer to the low, medium, and high severity of the cracks, respectively.

$$RFI = MIN \left(100, 100 - \left(\left(Avg_IRI - \left(\frac{1}{5} \right) \right) - 10 \right) \right) \quad (4.2)$$

where,

Avg_IRI = Average International Roughness Index (inches/mile)

$$RTI = MIN \left(100, 100 - \left(\left(R_{Avg} - \left(\frac{10}{0.125} \right) \right) - 10 \right) \right) \quad (4.3)$$

where,

R_Avg. = Average Rutting (inch.)

For flexible pavements, the composite index (PCI) is calculated using the following equation:

$$PCI = \frac{MAX\{MIN(RCI, ALCR, PTCH, RFI, RTI) \times AVG(RCI, ALCR, PTCH, RFI, RTI)\}}{0.85 SD(RCI, ALCR, PTCH, RFI, RTI)} \quad (4.4)$$

where,

ALCR = alligator cracking index;

PTCH = patch index; and

SD = standard deviation.

A summary of the condition data for the latest three collection cycles is illustrated in Figure 4.3. All the sections had a good to excellent pre-treatment conditions on average.

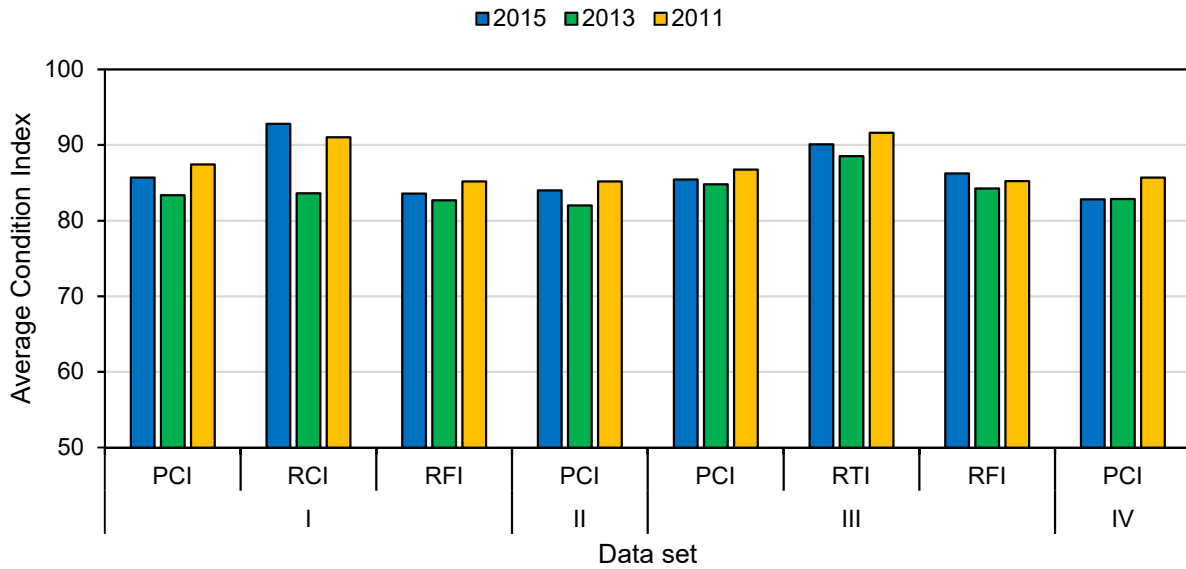


Figure 4.3. Pavement condition summary for different datasets

4.3. Traffic Data

Traffic data in terms of ADT for the selected projects were extracted from the PMS Highway Needs database 2017. The ADT of the sections ranged from 130 to 40,800. However, most of these surface treatments were found to be applied to pavements with low traffic. As shown in Figure 4.4, more than half of the sections had an ADT less than 1,000. Frequency distribution of the traffic data is presented in Figure 4.4.

The cumulative effects of traffic on pavement conditions over time were estimated using traffic (ADTX) load factor:

$$ADTX = ADT \times t_x \quad (4.5)$$

where,

ADT = Average daily traffic; and

t_x = Time from a previous major maintenance activity.

4.4. Climate Data

The temperature and precipitation data were extracted from the National Oceanic and Atmospheric Administration (NOAA) database. The 30-year averages were estimated by averaging the climatological values over the period ranging from 1980 to 2010. Geographic coordinates were used to assign temperature and precipitation values to each log mile of the treated sections. The mean annual precipitation ranged from 49 to 68 in. per year and the mean annual temperature varied from 62 to 71°F.

The cumulative effects of climate on pavement conditions over time were estimated using precipitation (AAPX) load factor:

$$AAPX = AAP \times t_x \quad (4.6)$$

Where,

AAP = Average annual precipitation; and

t_x = Time from a previous major maintenance activity.

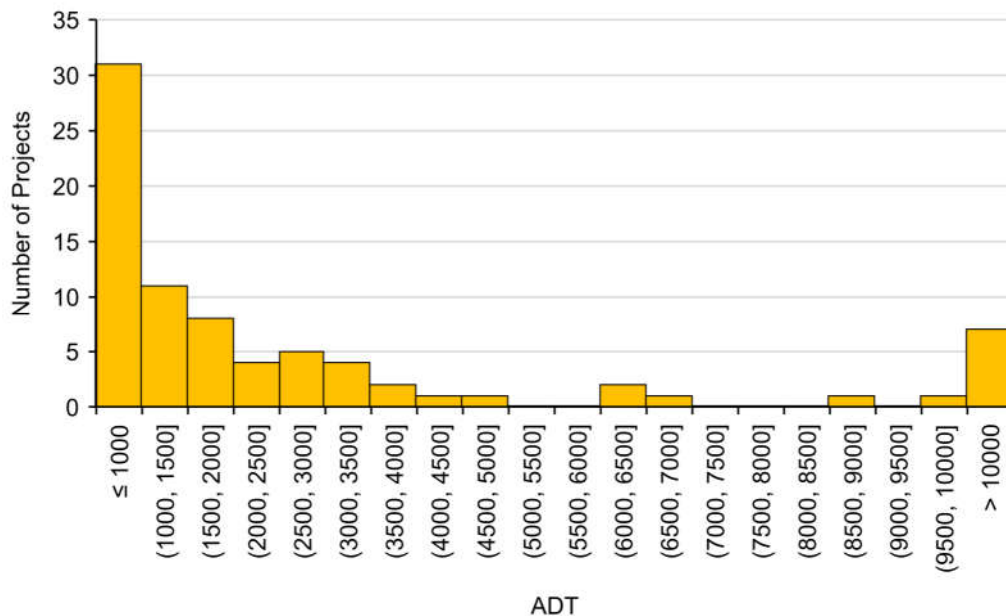


Figure 4.4. Frequency distribution of traffic data

4.5. Cost Data

Cost data for the projects were collected by reviewing the projects information database in the pavement management system. Figure 4.5 shows a typical project information report stored in the PMS. Total cost including the material and labor costs were divided by the number of lanes and length of the project to calculate the unit cost per lane-mile. Cost data for Louisiana indicated that chip seal and microsurfacing had an average cost of \$20,847 and \$47,710 per lane-mile, respectively.

```

*** PROJECT INFORMATION - PART 1 ***

CONTROL SECT: 022-05 LENGTH: 13.685 LAST JOB: 55 STATUS: C COMPLETE
PROJECT : 022-05-0053 FEDERAL #: NH 3007(502) CANCEL: _____
R/W UTIL PROJ: _____
ENGR PROJECT : _____ ACTIVITY CODE: _____
CONST PROJECT: _____ DOTD ACTIVITY: _____
LEAD PROJECT: 022-05-0053 # OTHER PROJECTS: 02 GOAL/SETASIDE: 1
ASSIGN FOR : DEBBIE BEARD DATE: 11/1/2007 BEG LOG MI: 9.955
DISTRICT: 58 PARISH: 30 -Lasalle LENGTH: 3.745 END LOG MI: 13.7
ROUTES: US 84 : _____ TYPE: M3 -Micro Surfacing : _____
PROJECT NAME : WHITEHALL - CATAHOULA PARISH LINE
LIMITS: BEGIN : LOCATED ON ROUTE US 84 FROM WHITEHALL
END : THE CATAHOULA PARISH LINE
PE/COOR: PANTERIA, GARY DIST/GANG: 58 201 WORK CAT: 300
DATES: BID : 9/24/2008 EST COST: 447,025 FINC SOURCE: ST/F
CTR : 11/13/2008 CONTRACT AMT: 411,250 SYSTEM CODE: 2
W.O.: 12/12/2008 PLANS? : PROPOSAL
F.I.: 7/10/2009 APPROVED COST: 348,706 FUNCT CLASS: 000
ACCP: 7/22/2009 FINAL COST: 355,738 CAP OUTLAY : C05
F.E.: 5/19/2010 CONTRACTOR: VANCE BROTHERS INC ERP PROJ:
ACTION: I A=ADD U=UPDATE D=DELETE I=INQUIRE C=CANCEL F=FINISH H.000760

```

(a)

```

*** PROJECT INFORMATION - PART 2 ***

PROJECT NUMBER: 022-05-0053 STATUS: C
CONSULTANT : _____ CONSULT PHONE : _____
FORMER PROJECT : _____ CONTRACT DAYS : 75 WORK/CL? W
1104 REQUESTED : _____ % TIME ELAPSED: 53
ABANDONMENT REQ'D: _____ % COMPLETE : 100
MAINTAINED BY : _____ % CHANGE : -7 AS OF: 9/23/2009
SENT TO GEN FILES: _____ ACTUAL DAYS : 40

ADDITIONAL ROAD SEGMENTS
CONTROL-SEC FROM TO
____
____
____
____
____
____
____

SMGR CONT ID: 022-05-0053
BRIDGE NOS: _____
WORK TYPE : MICROSURFACE
: _____ LETS CAT/SUB: PR/NI SPEC YR: 2006
ACTION: I U=UPDATE, I=INQUIRE 022-05-0053 PS Status: LET-Project Already Let

```

(b)

Figure 4.5. PMS project information database (a) part 1 and (b) part 2

CHAPTER 5. ANALYSIS AND RESULTS

5.1. Initial Effects

Initial effects of the applied treatments were evaluated in terms of performance jumps and deterioration rate reductions. Dataset I and III were used to quantify the initial benefits of chip seal and microsurfacing treatments respectively.

5.1.1. Performance Jump (PJ)

PJ results indicated that chip seal and microsurfacing were most effective in immediately improving the random cracking and rutting condition of the pavement respectively, where the slopes were found to be greater as compared to the other indices, see Figure 5.1, which is in line with the findings from previous studies (Hixon and Ooten 1993; Labi et al. 2006). For chip seal treatments, 97.9% of the log miles exhibited a positive PJ for RCI- with a mean of 17.4 ± 11.8 , whereas the mean for RFI- and PCI- ranged from 3.56 to 11.0. As summarized in Figure 5.1(a) and 5-2, chip seal had a negligible effect on improving the roughness of the pavements, which is consistent with the findings of other studies (Hall et al. 2002).

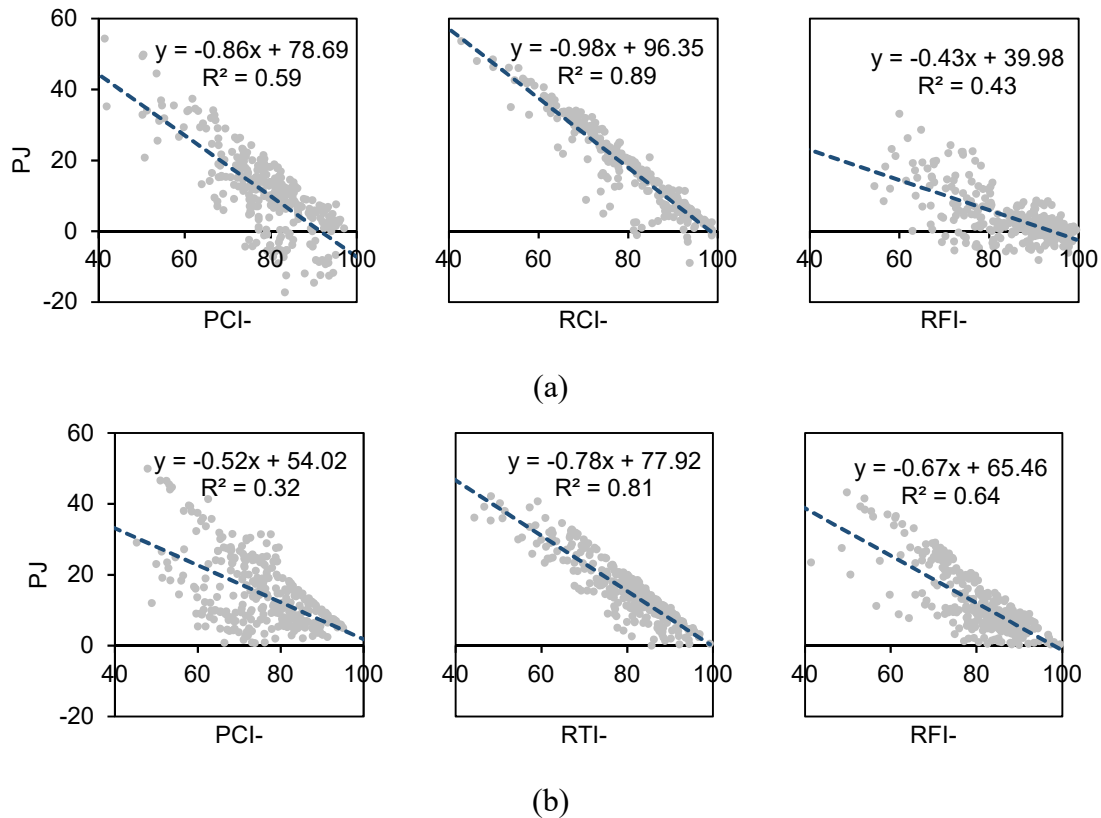


Figure 5.1. PJ due to (a) chip seal and (b) microsurfacing treatments as a function of the pretreatment condition of the pavement

Unlike chip seal, microsurfacing was found to be statistically significant in initially improving all the condition measures that are usually associated with this type of treatments. For microsurfacing treatments, PJ was observed to be highly correlated to the pre-treatment rutting condition of the pavements. 94.4% of the log miles exhibited a positive PJ for RTI- with a mean of 17.0 ± 14.4 , whereas the mean for RFI- and PCI- ranged from 11.4 to 15.2.

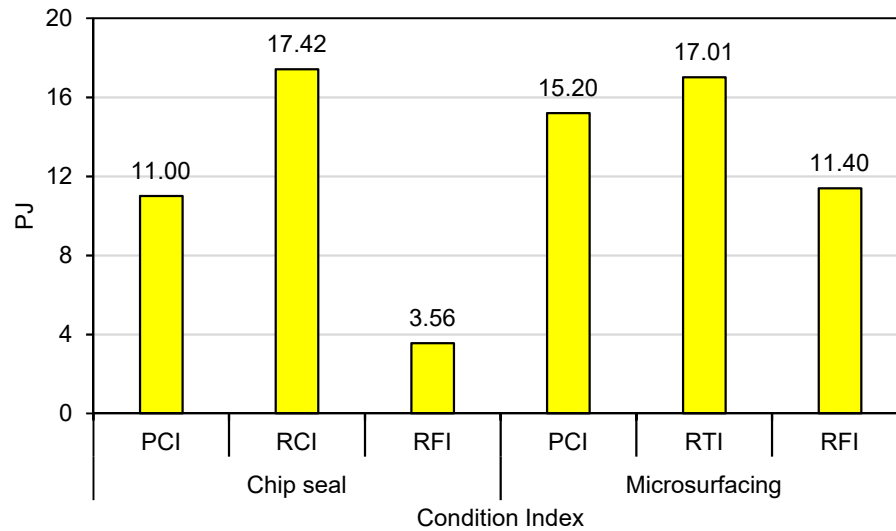
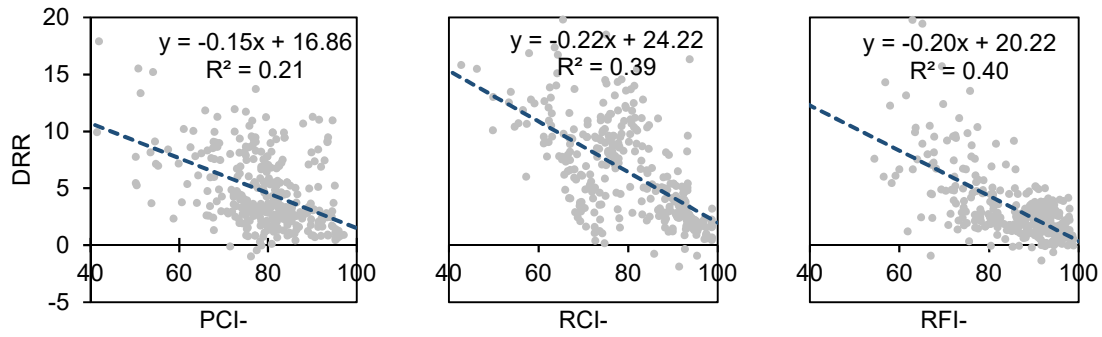


Figure 5.2. PJ in pavement condition indices due to treatment applications

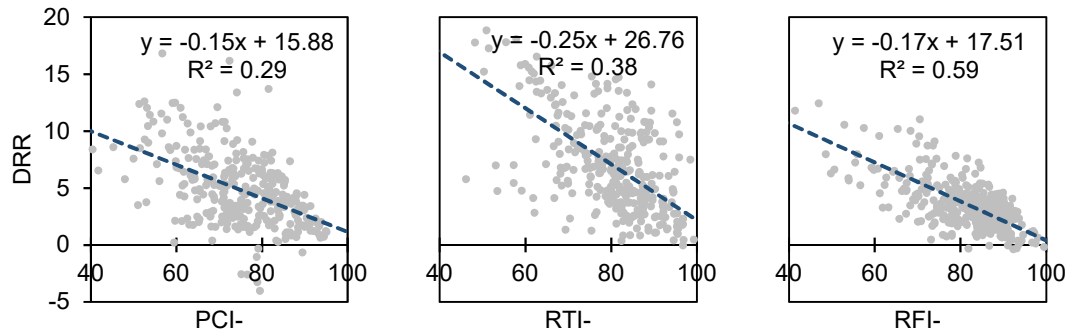
5.1.2. Deterioration Rate Reduction (DRR)

In line with the PJ results, DRR analysis also showed that chip seal and microsurfacing are most effective in immediately improving the random cracking and rutting condition of the pavement respectively. Chip seal slowed down the development of random cracks by 6.38 units/year and microsurfacing slowed down the deterioration of rutting condition by 7.43 units/year, see Figure 5.4. The correlation coefficients obtained for PCI- for both cases were found to be minimum. This is because the computation of the composite PCI index involves all the condition measures, some of which may not get affected due to the application of a specific treatment.

Although, both PJ and DRR showed a similar trend when plotted as a function of the pretreatment condition of the pavement, better co-relation values were observed for the PJ plots. Therefore, performance jumps may be considered as a better estimator of the initial effects of the treatments on the condition of the pavements.



(a)



(b)

Figure 5.3. DRR for (a) chip seal and (b) microsurfacing treatments as a function of the pretreatment condition of the pavement

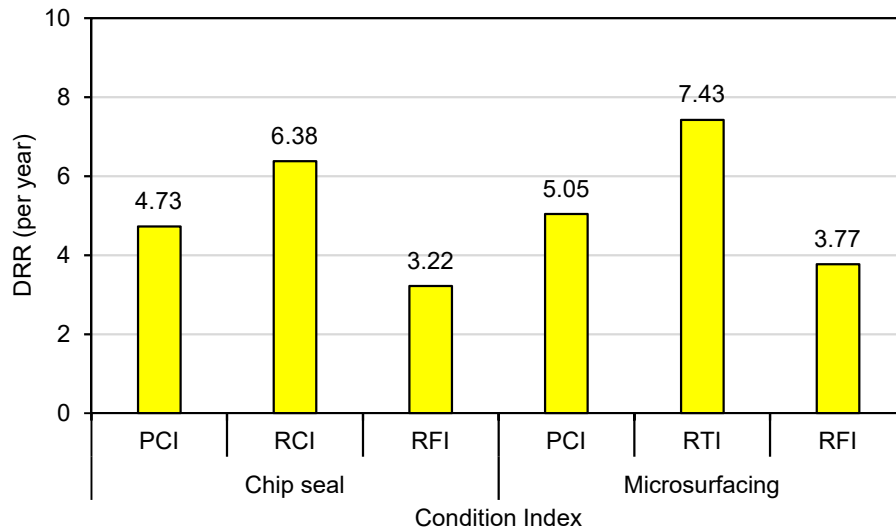


Figure 5.4. DRR in pavement condition indices due to treatment applications

5.2. Long-term Effectiveness (E)

Chip seal was found to be most effective in improving the random cracking condition of the pavement where a long-term effectiveness of 11.9% was observed with a slope of 0.92. Microsurfacing was 10.0 to 11.3% effective for improving the rutting and overall conditions of the pavement in the long-term where PCI exhibited the maximum slope of 0.97. However, as shown in Figure 5.5, 21.1% of the log miles for PCI- exhibited a negative E value. The Effectiveness as a function of pretreatment condition of the pavement can be useful in determining the upper limit beyond which applying a treatment will have a negligible effect on improving pavement performance. The estimated upper threshold values for an ineffective treatment application for both chip seal and microsurfacing are presented in Table 5.1.

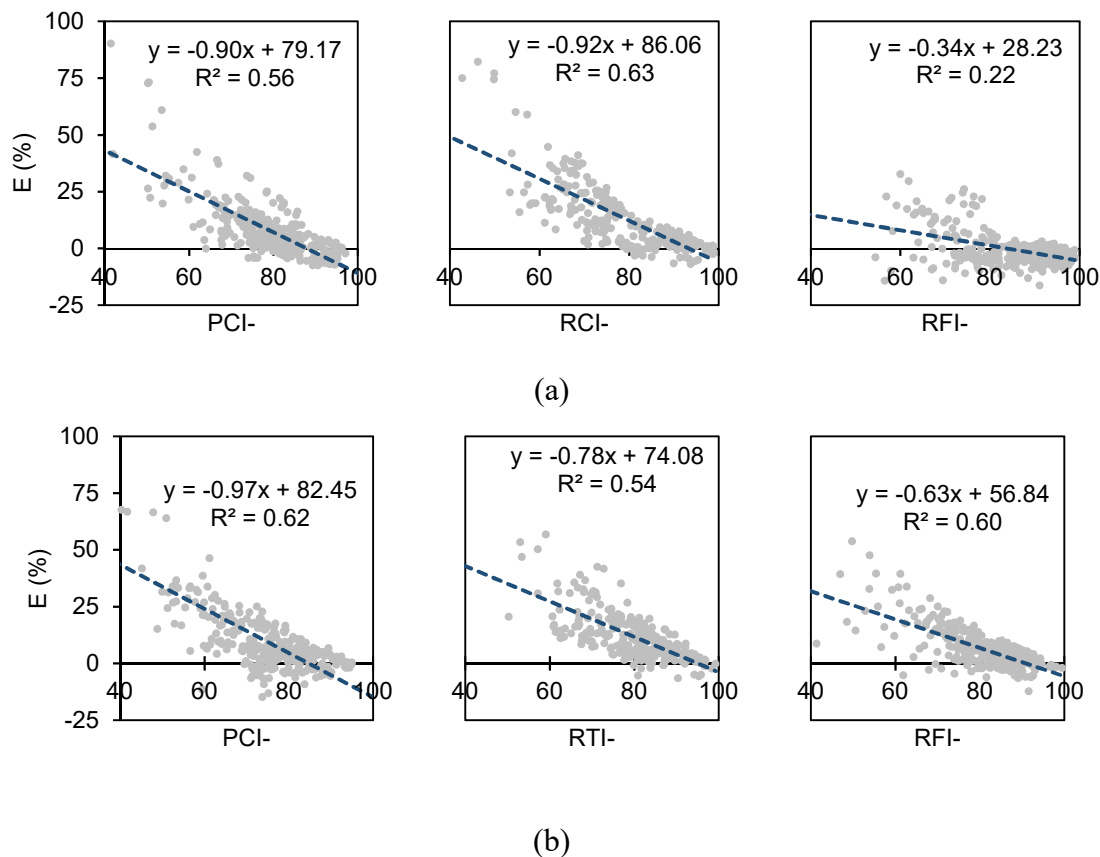


Figure 5.5. Effectiveness of (a) chip seal, and (b) microsurfacing treatments in the long term

For microsurfacing treatments, the effect of traffic load on the effectiveness shows that E increases up to a certain point and then starts to drop sharply as traffic load increases, see Figure 5-6(b). Treatment effectiveness is optimized when applied to pavements with ADTX less than 70,000. However, E did not exhibit a clear pattern for the sections with a chip seal treatment. For chip sealed sections, optimum effectiveness was observed when applied to pavements with ADTX of approximately 35,000. For both the cases, sections receiving precipitation (AAPX) less than 500 in. had a significantly higher efficiency as compared to the sections receiving higher precipitation load, although no definite relationship was observed. E increased with

increasing AC layer thicknesses up to a thickness of 10 in. for chip seal treatments, where an E of 13.2% was obtained and up to a thickness of 7 in. for microsurfacing treatments where the optimum E was estimated to be 15.7%.

Table 5.1. Estimated upper threshold of ineffective treatment application

Treatment	Pavement Condition Index	Upper threshold
Chip Seal	PCI	88
	RCI	93
	RFI	83
Microsurfacing	PCI	85
	RTI	95
	RFI	90

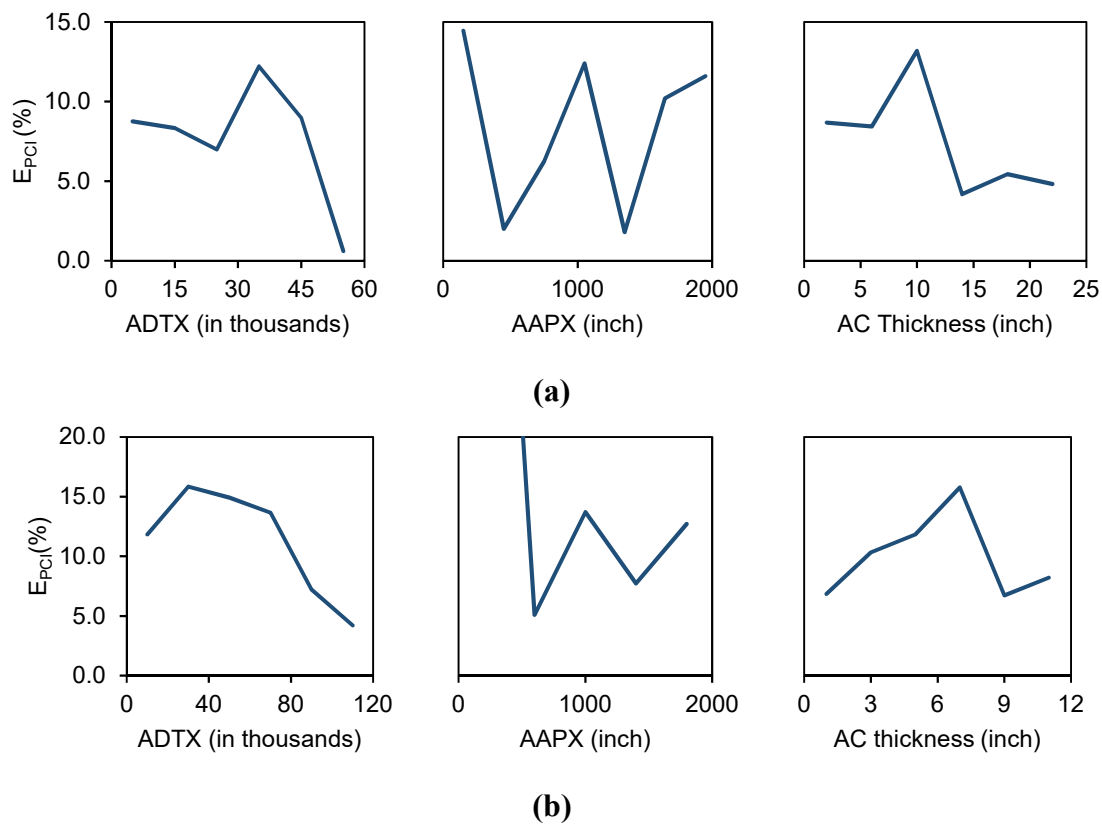


Figure 5.6. Effectiveness of (a) chip seal, and (b) microsurfacing treatment as a function of traffic, precipitation, and AC thickness

5.3. Service Life Extension (SLE)

Chip seal treatments, when applied to the pavements with PCI-<90, extended the service life of the pavements by 6.4 to 10.5 years. Whereas, microsurfacing was found to be extending the

service life of the pavements by 4.9 to 8.8 years. SLE in relation to the pretreatment condition of the pavements showed that SLE is optimized when applied to a pavement with PCI values ranging from 70 to 75 for chip seal applications and 80 to 85 for microsurfacing applications. Therefore, chip seal is more effective for pavements that are in a worse condition than the candidate projects for microsurfacing treatments, which is more effective for pavements with good existing condition. However, as shown in Figure 5.7, microsurfacing treatments applied to pavements with PCI->90 resulted in negative SLE, i.e., applying this treatment to pavements in excellent condition will cause more harm than benefits to the pavements.

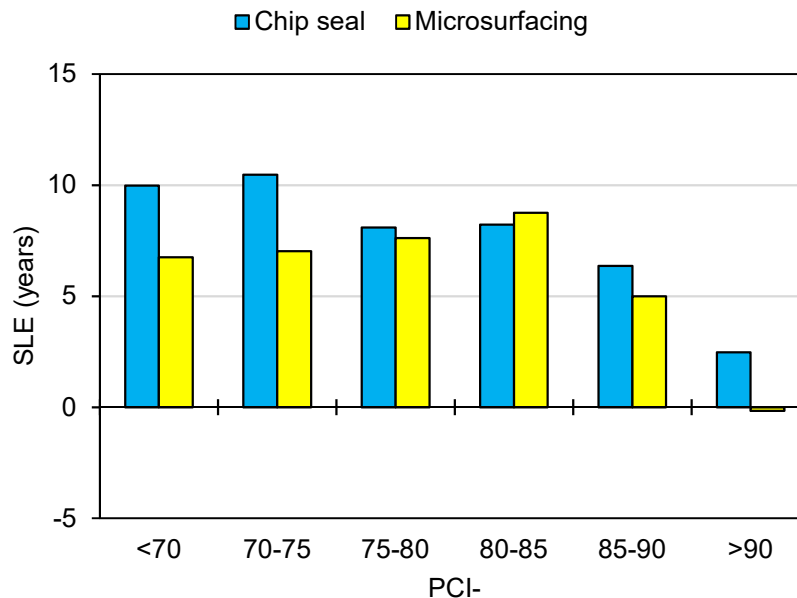


Figure 5.7. SLE as a function of pretreatment condition of the pavements

The treatments applied in different geographical locations in Louisiana did not show large variation in performance in terms of SLE, where the mean values ranged from 6.1 to 11.6 years for chip seal and 5.7 to 7.9 years for microsurfacing treatments. For all the districts, chip sealed performed better than microsurfacing except for district 2 where microsurfacing SLE exceeded chip seal by about 2 years. The effects of traffic load on the performance of the pavement were found to be similar to the effect of ADTX on the long-term effectiveness of the pavement. Microsurfacing had an optimum SLE of 8.8 years when ADTX values ranged from 50,000 to 70,000, whereas for chip seal treatments an optimum SLE of 8.9 years was observed for ADT<15,000. However, no definite trend in SLE was observed for varying AC layer thickness and precipitation load.

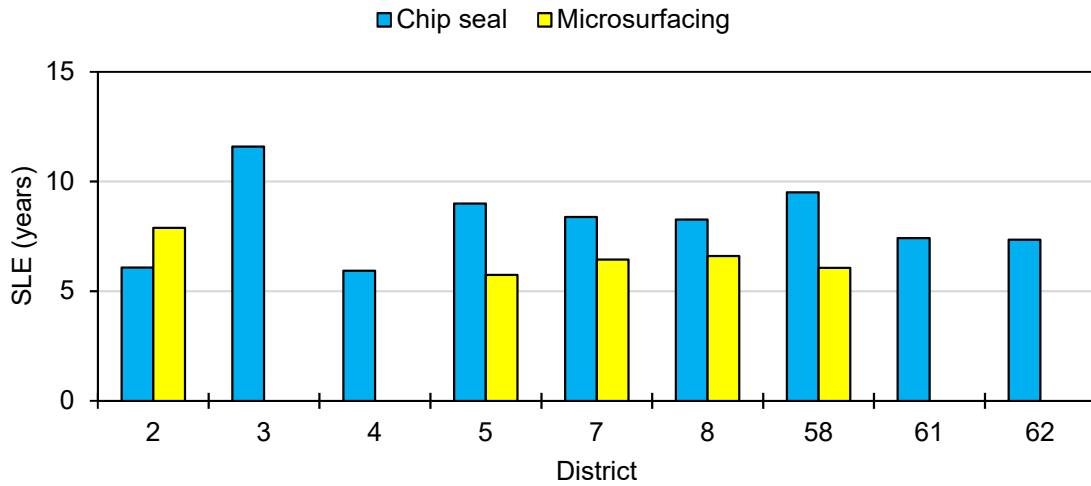
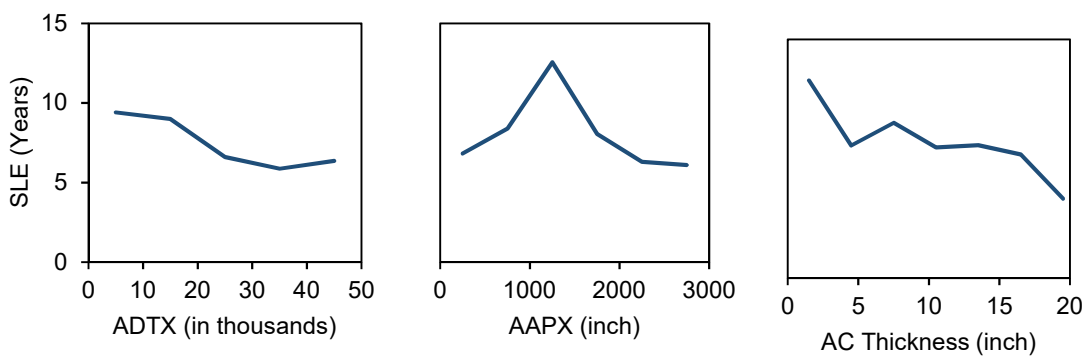
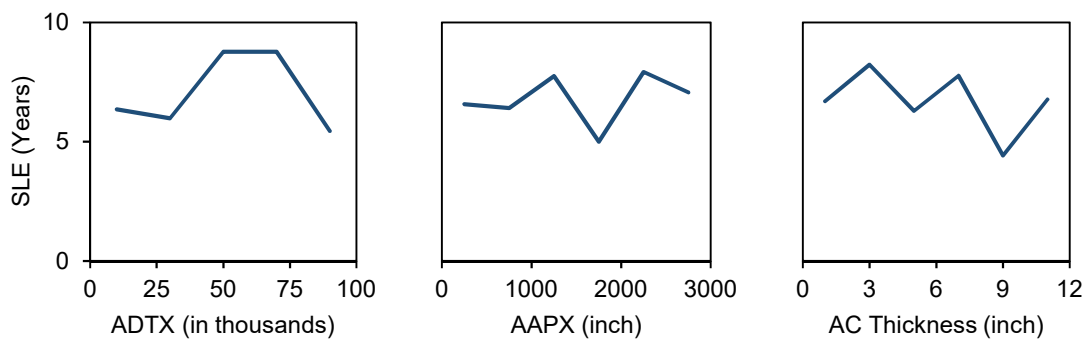


Figure 5.8. SLE due to the treatment applications at different districts in Louisiana



(a)



(b)

Figure 5.9. SLE as a function of traffic, precipitation and AC thickness for (a) Chip seal and (b) microsurfacing treatment

5.4. Treatment Cost-effectiveness (CE)

The average TNB were estimated to be 228.3 ± 124.9 PCI-years and 162.2 ± 88.8 PCI-years for chip seal and microsurfacing treatments respectively. It indicates that chip seals performed significantly better than the microsurfacing treatments when only the benefits are concerned. The variation of TNB with pretreatment condition is presented in Figure 5.10. Cost data for Louisiana indicated that chip seal and microsurfacing had an average cost of \$20,847 per lane-mile and \$47,710 per lane-mile, respectively. When compared on a project basis, all the projects with chip seal and microsurfacing were found to be cost-effective. However, less unit cost combined with the greater estimated benefits made chip seal economically more effective than the microsurfacing treatments, as can be seen from Figure 5.11. Both chip seal and microsurfacing were found to be the most cost-effective for district 8 and the least cost-effective for district 2. For all other districts, cost-effectiveness for chip seal was observed to be approximately the same.

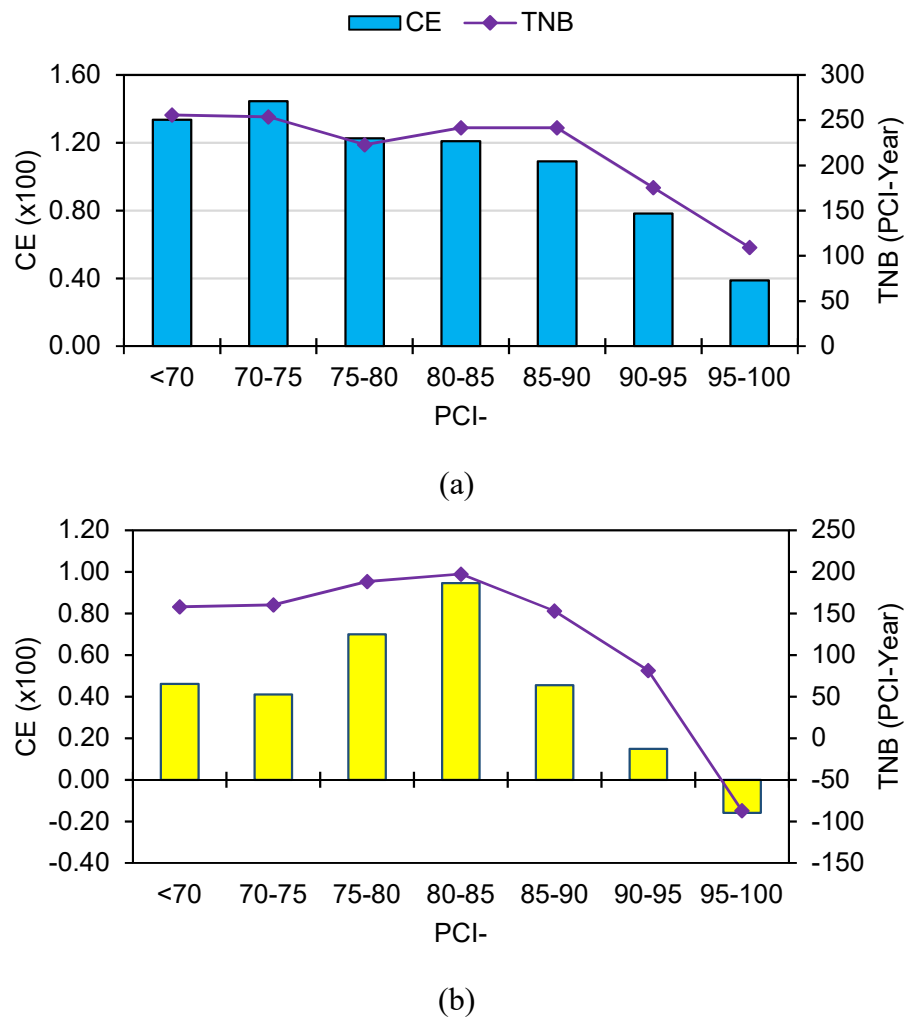


Figure 5.10. Cost-effectiveness of (a) chip seal and (b) microsurfacing treatments

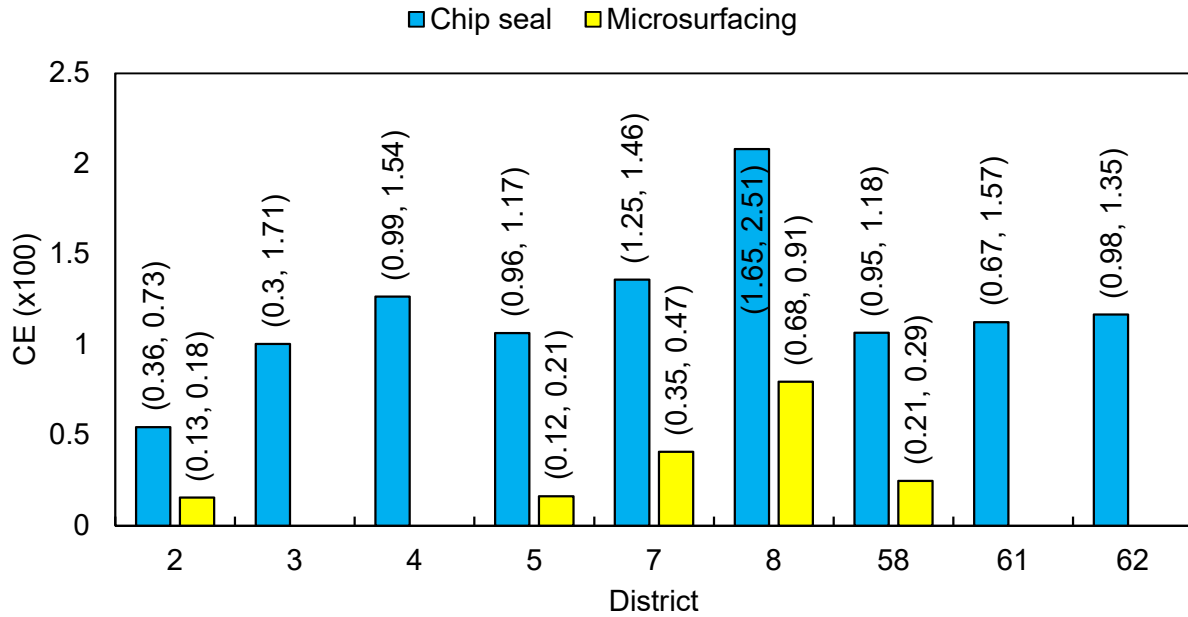


Figure 5.11. 95% confidence intervals for cost-effectiveness of chip seal and microsurfacing treatments throughout the state

As unit cost remained more or less the same for all the projects for a specific treatment type, CE followed the trend of TNB when the log miles were compared together on the basis of pavement conditions at the time of treatment. The performance in terms of both CE and TNB were found to be optimum for the log-miles having pre-treatment PCI values ranging from 70 to 75 for chip seal treatments and 80 to 85 for microsurfacing treatments, as shown in Figure 5-10. As observed for the other long-term measures such as E and SLE, the CE values dropped below 0 i.e. did not remain cost-effective, when microsurfacing was applied to locations with PCI>95.

5.5. Treatment Timing Optimization

In Louisiana, surface treatments are usually considered when the condition index of a pavement reaches a threshold. However, depending upon a single threshold value based on highway classification is highly arguable as factors such as pre-treatment condition, traffic, AC thickness, climate, and other exogenous factors influence the performance of these treatment activities significantly. Treatment timing is critical for treatment performance optimization.

Table 5.2 summarizes the treatment timing ranking for microsurfacing treatments in terms of pre-treatment condition of the pavement. ADT and AC thickness of the pavements were also found to be statistically significant in influencing the performance of chip seal and microsurfacing treatments. Therefore, weighting the results from E, SLE, and CE, a ranking of these factors was determined to facilitate a more accurate treatment timing and selection of the candidate projects.

Table 5.2. Optimum conditions for chip seal and microsurfacing treatments in Louisiana

Treatment	Rank	Factors		
		Pre-treatment condition	ADT	AC thickness (inch)
Chip seal	1	70-75	<1000	2-4
	2	75-80	1000-2500	5-7
	3	80-85	2500-5000	7-9
Microsurfacing	1	80-85	1500-3000	5-7
	2	75-80	<1500	3-5
	3	70-75	3000-5000	7-9

5.6. Effects on Moisture Damage

Due to the geographical setting of Louisiana, the pavements are highly susceptible to moisture damage. As both chip seal and microsurfacing seal the pavement surface, it will not be illogical to suspect that it may trap moisture underneath the pavement causing the moisture to gradually cause damage in the long-term. To assess whether chip seal and microsurfacing may contribute to moisture damage, a comparative study of the sections with moisture damage was conducted.

LaDOTD performed pavement coring throughout the state where a total number of 2,850 cores were collected from the different districts in Louisiana. To assess if moisture damage correlates with these treatment activities, the extent of moisture damage in treated and untreated sections were compared in each district by identifying the total number of stripped sections from the core reports. Table 5.3 summarizes the findings from the core reports. Figure 5.12 illustrates that the percentage of stripping in chip sealed sections is same as the stripping rate in the untreated sections, which indicates that using chip seal did not cause an increase in the percentage of stripped sections. Microsurfacing treatments, on the other hand, were found to be contributing towards moisture damage as the sections with microsurfacing treatments in all the districts exhibited 15-20% more stripping as compared to the untreated sections. It can also be inferred that the geographical location of the pavement plays a significant role in causing moisture damage to the pavements.

To understand what is causing the sections with microsurfacing treatments to get stripped at a greater rate, a comparative study of the sections with and without moisture damage was carried out. For a more comprehensive moisture damage analysis a total of 66 sections with chip seal and 21 sections with microsurfacing treatment were identified, where the treatments were applied between 2002 and 2008. Upon visual inspection of the extracted cores, it was observed that about one-third of the cores with chip seal and a quarter of the cores with microsurfacing treatments exhibited stripping. The core analysis results are summarized in Figure 5.13.

Table 5.3. Summary of the cores extracted from different districts in Louisiana

District	Total Cores Obtained	Untreated Sections		Sections with Chip Seal		Sections with Microsurfacing	
		Number of Cores	Cores with Stripping	Number of Cores	Cores with Stripping	Number of Cores	Cores with Stripping
2	258	237	16	2	0	12	2
3	417	377	75	26	8	4	1
4	496	340	38	101	10	7	0
5	285	159	53	124	45	10	3
7	204	157	65	25	10	9	5
8	389	299	59	69	12	23	7
58	204	131	20	105	29	16	6
61	289	246	53	36	7	13	5
62	308	223	23	76	9	6	1

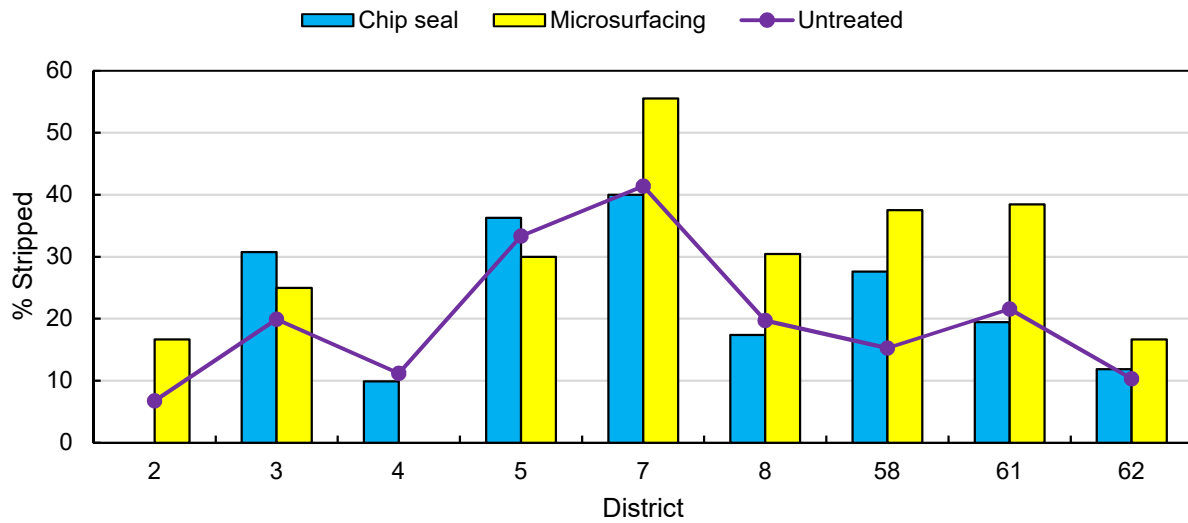


Figure 5.12. Extent of moisture damage in different districts of Louisiana

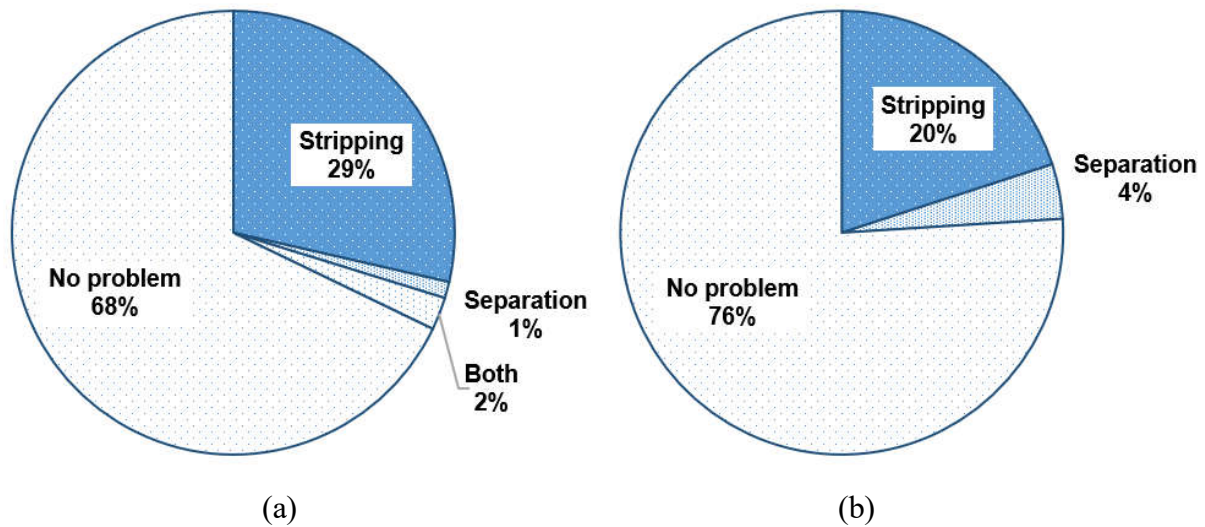


Figure 5.13. Summary of the core reports for moisture damaged sections with (a) chip seal and (b) microsurfacing

5.6.1. Moisture Damaged Sections with Chip Seal

Section 154-03

The road is located in Union Parish of District 5. It received a major rehabilitation in 1981 and carries an ADT of 780. The section had a length of 6.31 mile and the pavement structure consisted of a 6.5 in. AC layer and 12 in. red sand base layer on top of a brown clayey sand

subgrade. A chip seal treatment was applied in 2008. At the location of the core, the PCI was 88.7 and the average PCI along the section was 77.7. The section exhibits about 57 in. of annual rainfall and numerous stagnant water bodies along with an open channel were observed within a close proximity of the road, see Figure 5.13(a).

Section 188-03

The road is located in Allen Parish of District 7. It received a major rehabilitation in 1998 and carries an ADT of 920. The section had a length of 13.54 mile and the pavement structure consisted of a 7.5 in. AC layer and 6.5 in. red sand with small aggregates base layer on top of a brown sand subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 84.2 and the average PCI along the section was 91.1. The section exhibits about 62 in. of annual rainfall and the road is located within a 1-mile radius of two large water bodies i.e. Sweet lake and Willow lake are in close proximity, which may have significantly contributed to moisture damage underneath the pavement, see Figure 5.13(b).

Section 042-03

The road is located in Sabine Parish of District 8. It received a major rehabilitation in 1981 and carries an ADT of 740. The section had a length of 10.68 mile and the pavement structure consisted of a 7 in. AC layer and 26 in. red sand base layer on top of a tan sand subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 84.4 and the average PCI along the section was 77.4. The section exhibits about 54 in. of annual rainfall. No significant water bodies were found near the section although the extracted core was severely stripped as only about 2 in. out of 7 in. of AC could be recovered from the core, see Figure 5.13(c).

Section 039-01

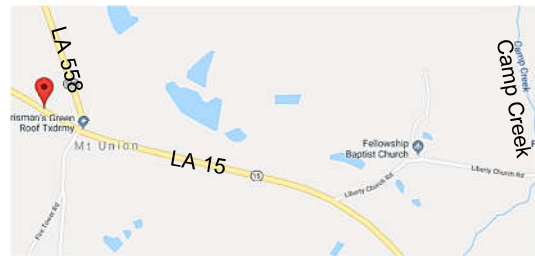
The road is located in Lasalle Parish of District 58. It received a major rehabilitation in 1999 and carries an ADT of 760. The section had a length of 4.74 mile and the pavement structure consisted of a 3.5 in. AC layer and 11 in. cement stabilized sand shell base on top of a sand subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 89.5 and the average PCI along the section was 82.9. The section exhibits about 58 in. of annual rainfall. The section had a good drainage condition and no significant waterbody was observed nearby except for Little Creek, see Figure 5.13(d).

Section 259-01

The road is located in East Feliciana Parish of District 61. It received a major rehabilitation in 1986 and carries an ADT of 1,600. The section had a length of 13.31 mile and the pavement structure consisted of a 13 in. AC layer on top of a light brown sandy clay subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 91.3 and the average PCI along the section was 83.7. The section exhibits about 62 in. of annual rainfall and most part of the section passes alongside the Amite river, which indicates that the section may have exhibited severe stripping due to a high groundwater table, see Figure 5.13(e).

Section 274-01

The road is located in Washington Parish of District 62. It received a major rehabilitation in 1985 and carries an ADT of 4,900. The section had a length of 10.25 mile and the pavement structure consisted of a 5 in. AC layer and 7 in. stabilized granular base on top of a clay subgrade. A chip seal maintenance was conducted in 2008. At the location of the core, the PCI was 71.5 and the average PCI along the section was 76.8. The section exhibits about 62 in. of annual rainfall and numerous water bodies around the section along with an open channel West Fork Burch Creek was observed within a close proximity of the road which may have significantly contributed to moisture damage underneath the pavement, see Figure 5.13(f).



(a) 154-03



(b) 188-03



(c) 042-03

Figure 5.14. Moisture damaged sections with chip seal treatment

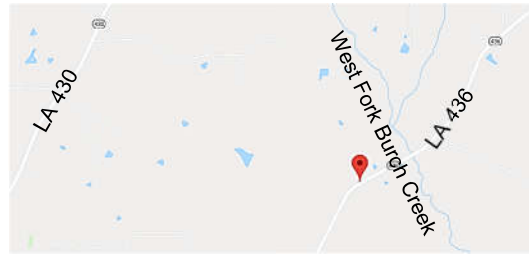
(figure cont'd.)



(d) 039-01



(e) 259-01



(f) 274-01

5.6.2. Moisture Damaged Sections with Microsurfacing

Section 146-01

The road is located in Avoyelles Parish of District 8. It received a major rehabilitation in 1987 and carries an ADT of 3,500. The section had a length of 12.29 mile and the pavement structure consisted of a 15 in. asphalt concrete (AC) layer on top of a brown clay subgrade. A microsurfacing maintenance was conducted in 2006. At the location of the core, the PCI was 91.7 and the average PCI along the section was 91.8. The section exhibits about 59 in. of annual rainfall and most part of the section passes alongside a stagnant waterbody within a 300 ft. proximity, which may have significantly contributed to moisture damage underneath the pavement, see Figure 5.14(a).

Section 193-01

The road is located in Cameron Parish of District 7. It received a major rehabilitation in 1991 and carries an ADT of 1,620. The section had a length of 13.38 mile and the pavement structure

consisted of an 8.5 in. AC and a 9.5 in. of crushed gravel with sand base on top of a clay subgrade. A microsurfacing maintenance was conducted in 2010. At the location of the core, the PCI was 91.4 and the average PCI along the section was 86.4. The section receives about 62 in. of annual rainfall. The core location is within half a mile radius of the Bayou Serpent river, which may indicate a high groundwater table.

Section 193-02

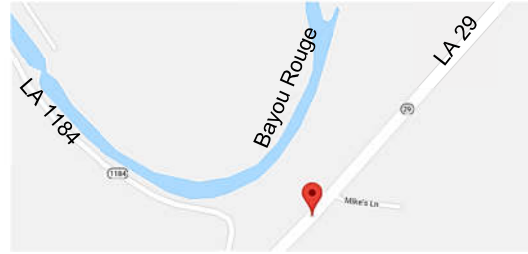
The road is located in Cameron Parish of District 7. It received a major rehabilitation in 1990 and carries an ADT of 2,600. The section had a length of 14.28 mile and the pavement structure consisted of a 10 in. AC and a 15 in. of sand base on top of a fat clay subgrade. A microsurfacing maintenance was conducted in 2010. At the location of the core, the PCI was 85.9 and the average PCI along the section was 90.7. The section receives about 62 in. of annual precipitation. However, no significant water bodies were found near the section.

Section 374-03

The road is located in Avoyelles Parish of District 8. It received a major rehabilitation in 1966 and carries an ADT of 510. The section had a length of 18.42 mile and the pavement structure consisted of a 7 in. AC layer on top of a red silty sand subgrade. A microsurfacing maintenance was conducted in 2003. At the location of the core, the PCI was 81.5 and the average PCI along the section was 88.4. The section receives about 57 in. of annual precipitation. Numerous numbers of small water bodies were found near the section as it is located very close to the Red River.

Receiving a major rehabilitation in 1980 and 90's, these pavements have carried enormous traffic and climate loads throughout their lifetime. The comparative study revealed that despite having a good to excellent PCI rating, these sections have significant moisture damage underneath the pavement surface. Compared to the age of these pavements from a previous major rehabilitation activity, chip seal and microsurfacing treatments were applied only recently. No definite evidence of chip seal or microsurfacing being the primary contributor of moisture damage could be found.

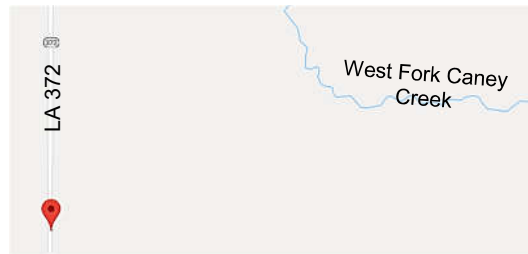
To investigate the excessive stripping rate due to microsurfacing, stripped sections with microsurfacing treatments were compared to the sections receiving similar microsurfacing treatments that exhibited no moisture-induced damage. The results show that the sections that exhibited stripping had lower AC thicknesses as compared to the sections with no stripping by 3 inches on average, see Figure 5.16. The thickness of the base layer showed high variability but when properties of these layers were looked into, it was observed that none of the bases of the stripped sections were stabilized, whereas 72.2% of the sections with no moisture damage had either a cement or lime stabilized base as shown in Figure 5.17. Both categories of the pavements received similar annual precipitation throughout their service life. Based on the observed differences, no definite conclusion could be drawn on microsurfacing causing these pavements to get stripped at a higher rate. A more in-depth research is needed to quantitatively assess the effects of microsurfacing on moisture damage especially in areas with high groundwater table.



(a) 146-01



(b) 193-01



(c) 193-02



(d) 374-03

Figure 5.15. Moisture damaged sections with microsurfacing treatment

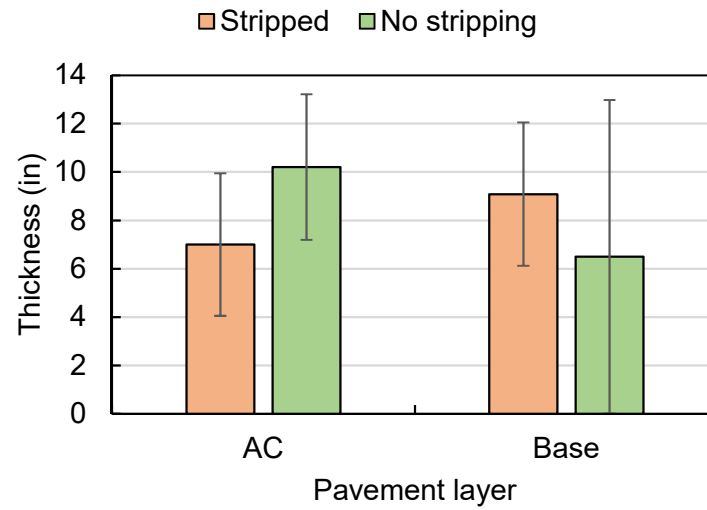


Figure 5.16. Layer thicknesses for the sections with microsurfacing treatment

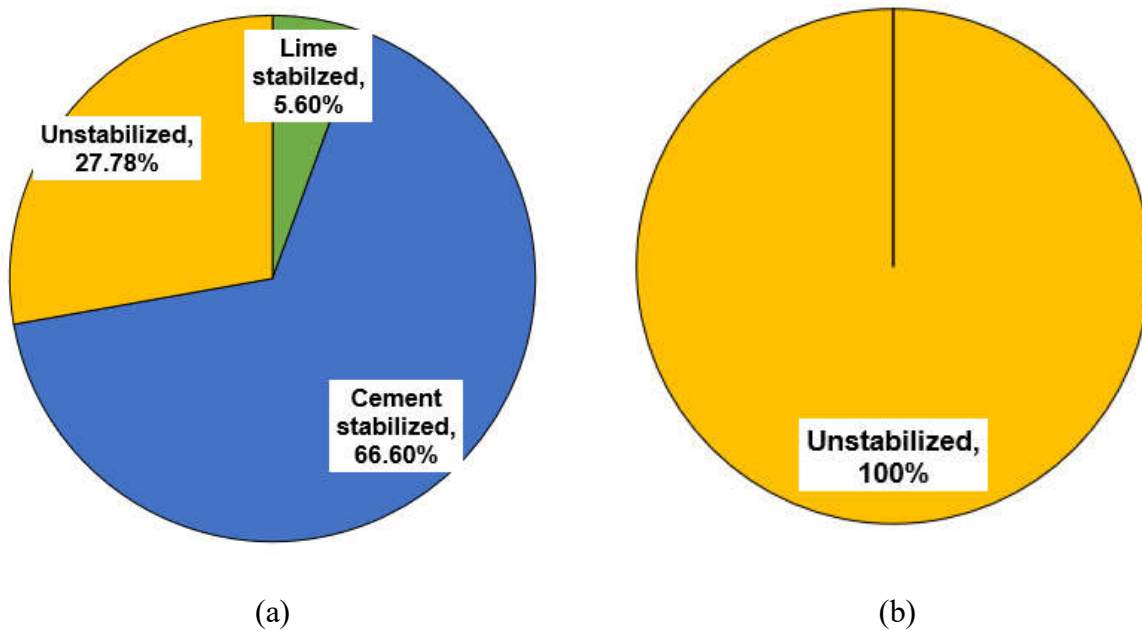


Figure 5.17. Base layer properties for sections with microsurfacing exhibiting (a) no stripping, and (b) stripping

CHAPTER 6. SUMMARY AND CONCLUSIONS

6.1. Summary

The study presented in this thesis evaluated the effectiveness of chip seal and microsurfacing treatments in a setting where pavements are highly vulnerable to moisture damage due to heavy rainfall and a high groundwater table. The primary objective of this study was twofold. First, the short and long-term performances of chip seal and microsurfacing treatments were evaluated as related to the pre-treatment conditions of the pavement. Performance curves were developed to assess the cost-effectiveness of the treatment. Effectiveness models in conjunction with the cost-benefits of the projects were used to identify the optimum timing for this preventive maintenance activity. Second, treated sections were evaluated to assess whether chip seal or microsurfacing significantly contribute to moisture damage.

To accomplish the objectives, the field performance of 51 flexible pavements with chip seal and 28 flexible pavements with microsurfacing treatment were monitored for at least eight years. Log-miles that satisfied acceptance criteria were selected for a detailed performance and economic evaluation. Performance curves for each of the selected log-miles were developed by modeling pavement conditions as a function of time. Long-term pavement performance data were used to quantify the benefits of chip seal and microsurfacing treatments in terms of the appropriate pavement performance indicators for the specific treatment type. Based on the quantified benefits, a ranking of factors affecting the performance of these treatments was determined to facilitate a more accurate selection of the candidate projects and to optimize the timing of treatment activities.

6.2. Conclusions and Findings

With respect to chip seal, the following conclusions may be drawn:

- Chip seal treatments were found to be most effective in immediately improving the random cracking condition of the pavements where it instantly improved RCI by about 17.4 units and slowed down the deterioration rate by about 6.38 units/year.
- Chip seal had a negligible effect on instantly improving the roughness condition of the pavements. It improved RFI by only 3.5 units and 29.6% of the log-miles exhibited a negative jump in roughness due to the application of chip seal.
- The long-term effectiveness of chip seal was estimated to be 11.9% for random cracking condition of the pavement. The effectiveness results also indicated that chip seal treatments become unrewarding if applied to a pavement with PCI, RCI and RFI values greater than 88, 93 and 83, respectively.
- Chip seals extend the service life of pavements by 6.5 to 10.4 years on average. Pretreatment condition, traffic, and AC layer thickness were found to be statistically significant in influencing the SLE due to chip seal application.
- All the projects with chip seal treatments were found to be cost-effective. Due to low unit costs chip seal treatments were observed to be economically more effective than the microsurfacing treatments.
- The performance of chip seal treatments was found to be optimum at $70 < PCI^- < 75$, $ADT < 1000$, and $2'' < AC \text{ thickness} < 4''$.

- Geographical location of the pavements was found to have a significant influence on the moisture-induced damages on the pavements and no definite evidence was found indicating chip seal being the primary factor contributing to these damages.

With respect to microsurfacing, the following conclusions may be drawn:

- Microsurfacing, in the short-term, was most effective in improving the rutting condition of the pavements where it instantly improved RTI by about 18.1 units and slowed down the deterioration rate by about 7.43 units/year. It also slowed down the deterioration of roughness condition by 3.7 units/year.
- The long-term effectiveness of microsurfacing treatments ranged from 10.0-11.3% for rutting and overall condition of the pavement. The effectiveness results also indicated that the treatments are not beneficial if applied to a pavement with PCI, RTI, and RFI values greater than 85, 95 and 90 respectively.
- Microsurfacing treatment extended the service life of the pavements by 4.9 to 8.8 years on average. Traffic and AC layer thickness were found to be statistically significant in influencing the SLE of the pavements.
- Microsurfacing was found to be cost-effective. However, applying the treatment with $PCI > 90$ will cause a reduction in economic benefits.
- The optimum conditions for microsurfacing treatments were estimated as $80 < PCI < 85$, $1500 < ADT < 3000$, and $5" < AC \text{ thickness} < 7"$.
- Although the sections with microsurfacing treatments were observed to have a higher percentage of moisture damage as compared to the untreated sections, no significant evidence was found indicating microsurfacing being the primary factor contributing to moisture damage in these pavements.

6.3. Recommendations

The findings of this study should be adopted by state agencies to set guidelines for future maintenance activities involving chip seal and microsurfacing. To optimize the performance of these surface treatments it is recommended that these treatments are used in a preventive maintenance mode at the network level instead of randomly applying them to pavements in poor condition. In addition, the recommended treatment timing in terms of pre-treatment condition, traffic and pavement layer thicknesses should be incorporated into the existing pavement performance models that trigger the need for a rehabilitation project. The following recommendations should also be considered in future research to optimize the use of these surface treatments:

- With respect to microsurfacing, further research is needed to assess the effects of this treatment on moisture damage especially in areas with high groundwater table.
- An in-depth assessment of the effects of these surface treatments on moisture damage should be conducted considering the factors such as precipitation, evaporation, and permeability of the pavement layers.
- Other aspects of the treatment methods including material characteristics of AC, aggregates, and application rates may also have significant effects on the performance of the treatment activities, in addition to the factors considered in this study.
- In future studies, the effects of the methods of treatment application should be investigated.

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